प्रभावी उपचार विधि का अभिकल्पन

4

प्रयोगशाला स्तर पर चारकोल अवशोषण कॉलम का यांत्रिक अभिकल्पन एवं प्रदर्शन मूल्यांकन

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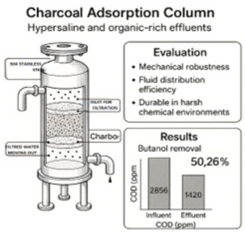

सक्रिय कार्बन अवशोषण विधि के लिए चारकोल कॉलम का अभिकल्पन एवं प्रदर्शन।

सारांश

इस अध्ययन में, 304 ज़ंगरोधी इस्पात से निर्मित प्रयोगशाला-स्तर के चारकोल अधिशोषण कॉलम के अभिकल्पन एवं प्रदर्शन मूल्यांकन को प्रस्तुत किया गया है, जो अतिलवणीय एवं कार्बनिक-समृद्ध अपशिष्टों का निपटान करने हेतु अभियंत्रित है। कॉलम का अभिकल्पन यांत्रिक मजबूती एवं द्रव वितरण दक्षता पर बल देता है, जिसमें अनुकूलित ज्यामिति तथा रिक्त स्थान शामिल हैं। विश्लेषणात्मक प्रतिबल-विकृति विश्लेषण तथा परिमित तत्व अनुकरण के माध्यम से यांत्रिक अखंडता को मान्य किया गया । ज़ंग प्रतिरोधी इस्पात कठोर रासायनिक वातावरण में दीर्घकालिक स्थायित्व सुनिश्चित करता है। कॉलम ने जलीय सोडियम क्लोराइड घोल से ब्यूटेनॉल के प्रभावी अपनयन को दर्शाया, जिससे रासायनिक ऑक्सीजन की मांग (सीओडी) 2856 पीपीएम से घटकर 1420 पीपीएम और अपनयन की दक्षता 50.26% हो गई। ये परिणाम औद्योगिक अपशिष्ट जल उपचार के लिए एक स्थायी एवं किफ़ायती समाधान के रूप में चारकोल-आधारित अवशोषण की क्षमता को उजागर करते हैं।

Effluent Treatment Method Design

4

Mechanical Design and Performance Evaluation of a Laboratory Scale Charcoal Adsorption Column

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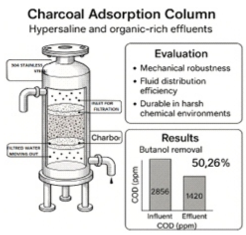

Design and Performance of Charcoal column for Activated Carbon Adsorption Method.

ABSTRACT

This study presents the design and performance evaluation of a laboratory-scale charcoal adsorption column constructed from 304 stainless steel, engineered to withstand hypersaline and organic-rich effluents. The column's design emphasizes mechanical robustness and fluid distribution efficiency, incorporating optimized geometry and void spaces. Mechanical integrity was validated through analytical stress-strain analysis and finite element simulations. The corrosion-resistant stainless steel ensures long-term durability in harsh chemical environments. The column demonstrated effective removal of butanol from an aqueous sodium chloride solution, reducing chemical oxygen demand (COD) from 2856 ppm to 1420 ppm a removal efficiency of 50.26%. These results highlight the potential of charcoal-based adsorption as a sustainable and economical solution for industrial wastewater treatment.

KEYWORDS: *COD, Corrosion-resistant, Charcoal,* Wastewater

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Introduction

Activated carbon adsorption columns are vital in environmental remediation and process engineering, particularly for the removal of contaminants from air, water, and industrial effluents [1]. While adsorption efficiency is key to performance, mechanical integrity becomes critical when transitioning from laboratory-scale prototypes to full-scale industrial systems [2,3].

This study focuses on the structural and operational analysis of a charcoal-packed adsorption column fabricated from 304 stainless steel. The column was specifically designed to withstand internal pressures generated by fluid flow and packed bed resistance. Mechanical evaluations including analytical calculations and finite element simulation were conducted to assess hoop and axial stresses, ensuring structural stability under operational loads [4,5].

304 stainless steel was selected for its excellent corrosion resistance, mechanical strength, and suitability for harsh chemical environments, such as those containing organic solvents and hypersaline effluents. The column geometry and packing configuration were optimized to ensure uniform fluid distribution, minimize channeling, and accommodate mechanical stresses.

The column demonstrated effective removal of butanol from an aqueous sodium chloride solution, with the chemical oxygen demand (COD) decreasing from 2856 ppm to 1420 ppm achieving a filtration efficiency of 50.26%. These results underscore the potential of charcoal-based adsorption systems as both mechanically resilient and environmentally sustainable solutions for industrial wastewater treatment.

Materials and Methods

Column configuration and material properties

Material: 304 Stainless Steel – chosen for its excellent corrosion resistance and mechanical strength.

Geometry:

i. Length: 0.609 m

ii. Internal Diameter: 2.54 cm

iii. Total Internal Volume: 0.0002943 m^3

iv. Charcoal Bed Volume: 0.00024531 m^3

v. Top and Bottom Free Spaces: 0.0000490625 m^3 and 0.0000294375 m^3, respectively.

Load Considerations: The packed charcoal bed density (98.125 g per column) translates into an approximate bulk density, yielding a distributed load over the column's base. The design must account for static loads from the bed as well as dynamic loads from inlet pressure fluctuations.

Flow Distribution and Support Elements

Perforated Plate:

i. Diameter: 2.54 cm

ii. Mesh Aperture: 1 mm

These plates are employed at both the inlet and outlet to ensure uniform distribution across the charcoal bed, helping to mitigate localized overloading and potential mechanical failures.

Mechanical Analysis

The mechanical analysis of the charcoal column includes theoretical stress/strain calculations, finite element analysis (FEA) simulations, and mechanical integrity assessments of both the stainless steel body and the perforated plates.

Analytical stress analysis

For a cylindrical column subject to radial pressure from the packed bed and potential dynamic pressures from fluid flow, the hoop stress (σ_h) and axial stress (σ_a) are of primary concern. These are given by:

Hoop Stress (σ_h) = $(P.r)/t$ and Axial Stress (σ_a) = $(P.r)/2t$

where

P = pressure exerted by the packed bed and fluid flow,

r = internal radius (0.0127 m),

t = wall thickness of the column (assumed based on design; e.g., 1–2 mm).

For instance, if an internal pressure of 50 kPa is assumed during peak operation, the calculated stresses (0.635 MPa and 0.3175 MPa) ensure that the design remains within the allowable stress limits for 304 stainless steel, typically around 205–240 MPa in bending and tensile modes.

The Fig.1 demonstrates the cylindrical geometry, indicating the internal radius, wall thickness, and load-induced stress vectors. The figure highlights the hoop (circumferential) and axial stresses with annotated equations.

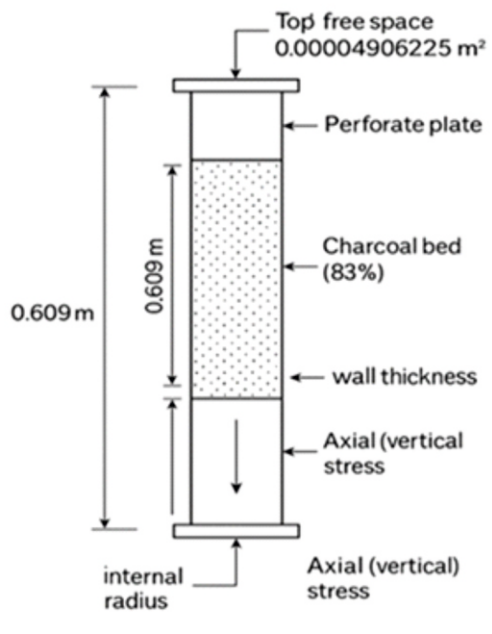

Fig. 1: Conceptualized Charcoal column geometry.

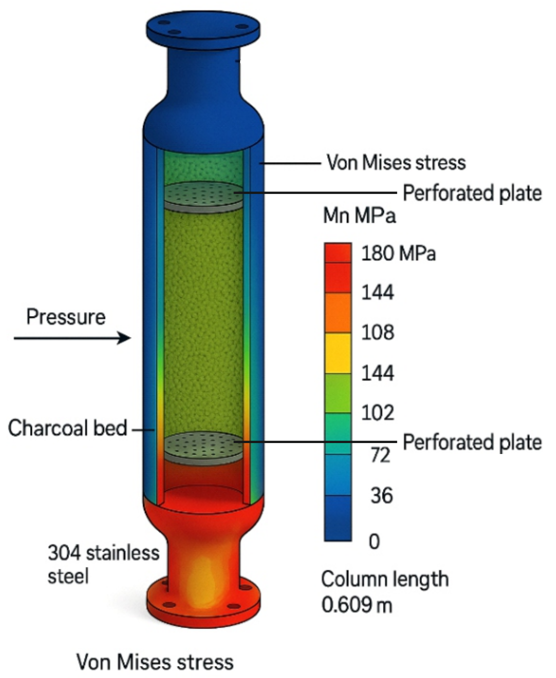

Fig.2: FEA Analysis of Charcoal column using Ansys.

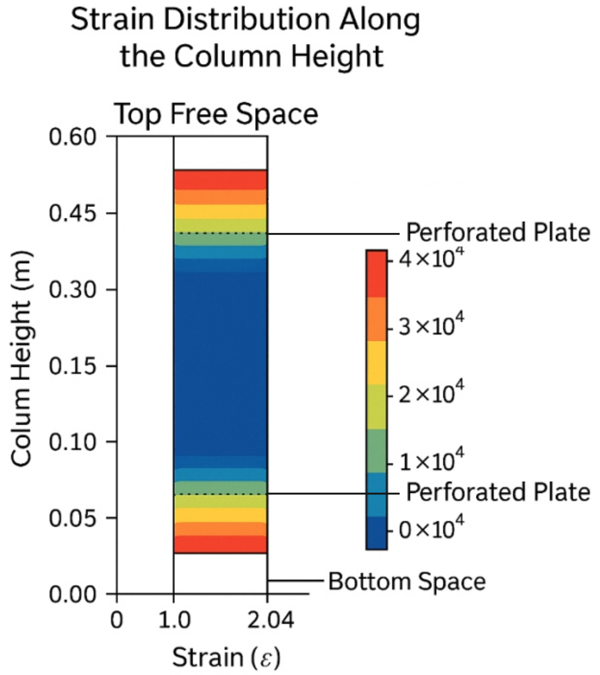

Fig.3: Strain Distribution in charcoal column using Ansys.

Finite element analysis (FEA) simulation

Complementing the analytical calculations, an FEA simulation was conducted to visualize the stress distribution over the column wall under operational load conditions. The simulation assumed:

- Boundary Conditions: Fixed constraints at the base; distributed pressure corresponding to the packed bed and transient flow conditions.
- Stress Concentration Areas: Around the perforated plates and the free spaces.

A color-coded stress in Fig.2 of the column wall and support plates is provided. The diagram shows peak stress regions, with particular attention to the transitional zones near the perforated plates. This simulation validates that the maximum stress levels remain below the yield strength of 304 stainless steel, confirming the structural reliability under both static and dynamic loads.

Strain analysis and deformation

Small deformations are expected due to the stiffness of stainless steel. Strain (ϵ) analysis based on Hooke's Law ($\epsilon=\sigma/E$) indicates that the maximum computed strains are in the order of 10^{-4} to 10^{-3}, where E (Young's modulus) for 304 stainless steel is approximately 193 Gpa. Both analytical and simulated strain values confirm negligible deformation, ensuring the integrity of the adsorption process.

The strain distribution along the column height in Fig.3 localized strain values near structural discontinuities, such as the edges of the perforated plates and the interfaces of the free spaces, reinforcing the robustness of the design.

Filtration Efficiency of Charcoal filter bed

The charcoal adsorption column demonstrated effective removal of butanol traces from an aqueous sodium chloride solution, resulting in a substantial reduction in chemical oxygen demand (COD). The initial COD of the solution was 2856 ppm, primarily attributed to the presence of organic butanol compounds. Following treatment through the charcoal-packed column, the COD was reduced to 1420 ppm, indicating significant adsorption of organic contaminants by the charcoal media. This corresponds to a filtration efficiency of approximately 50.26%, highlighting the potential of charcoal-based adsorption as a cost-effective and environmentally sustainable method for treating organic-laden industrial effluents.

$$\text{Filtration Efficiency (\%)} = \frac{(Initial\ COD - Final\ COD)}{Initial\ COD} \times 100$$

$$= \frac{(2856-1420)}{2856} = 50.26\ \%$$

Discussion

The combined analytical and numerical results validate the mechanical viability of the charcoal adsorption column design. The low induced stress and strain levels confirm that both the column wall and the perforated support plates can safely withstand operational pressures without risk of permanent deformation. Uniform stress distribution across the structure minimizes the potential for mechanical failure or leakage an essential factor for scale-up in industrial applications [6]. The incorporation of free spaces enhances flow uniformity and adsorption contact without compromising structural integrity, aligning with prior findings on packed-bed reactor optimization [7,8].

The system also demonstrated effective contaminant removal. The column achieved a filtration efficiency of approximately 50.26%, reducing the COD of a butanol-contaminated saline solution from 2856 ppm to 1420 ppm. This performance is consistent with other studies reporting the efficacy of activated carbon in removing organic solvents from aqueous solutions. The favorable flow dynamics supported by the optimized geometry likely contributed to improved mass transfer and adsorption efficiency, a factor well-documented in porous media flow studies [9].

Finite element analysis (FEA) corroborated theoretical stress predictions, reinforcing confidence in the column's mechanical design and long-term reliability [10]. Collectively, the analysis highlight the potential of this system as a scalable, dual-performance solution for industrial wastewater treatment offering both structural durability and environmentally sound treatment of hypersaline, organic-laden effluents.

Conclusions

The designed charcoal adsorption column successfully integrates mechanical integrity with effective contaminant removal performance. The comprehensive mechanical analysis encompassing stress and strain evaluations through both analytical methods and finite element analysis confirms that the column, fabricated from 304 stainless steel, is structurally sound and capable of withstanding the operational pressures encountered during treatment of hypersaline, organic-laden effluents.

In addition to mechanical reliability, the column demonstrated notable treatment efficiency, achieving a 50.26% reduction in chemical oxygen demand (COD) when processing a butanol-contaminated saline solution. This level of filtration efficiency highlights the potential of activated charcoal as a practical medium for removing organic pollutants under challenging chemical conditions.

Further experimental validation, including pressure drop measurements and dynamic load testing, is recommended to fully characterize performance under real-world operational scenarios. The approach outlined in this study provides a robust foundation for scaling the system for industrial wastewater treatment applications, combining structural durability with environmentally sustainable treatment capabilities.

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