

**EFFECT OF CATALYST PARTICLE SHAPE AND BED
PACKING TECHNIQUE ON HYDRODYNAMICS OF TRICKLE
BED REACTOR**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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BED REACTOR**

by

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

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CERTIFICATE

This is to certify that the thesis entitled '**Effect of Catalyst Particle Shape and Bed Packing Technique on Hydrodynamics of Trickle Bed Reactor**' being submitted by **Ms. Aashna Suneja** to the Indian Institute of Technology-Delhi for the award of the degree of **Doctor of Philosophy (Ph.D.)** is a record of bona fide research work carried out by her under my guidance and supervision. The research report and results presented in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

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A handwritten signature in black ink, written in a cursive style. The name 'Aashna Suneja' is written on two lines, with a horizontal flourish under the second line.

Aashna Suneja

Abstract

The Trickle Bed Reactor (TBR) is the indispensable workhorse for deep hydroprocessing, yet its efficiency is severely undermined by persistent hydrodynamic failures that prevent the required near-100% catalyst utilization demanded by modern ultra-low sulfur fuel standards. The fundamental challenge lies in the industrial reality that TBRs must use complex non-spherical catalysts (trilobes) and imperfect mechanical loading techniques, while existing design models remain reliant on outdated assumptions of homogeneous beds and idealized spherical particles. This research attempts to resolve this critical industrial bottleneck by establishing the first definitive, multi-scale relationship between the catalyst's geometric properties and the resulting fluid flow dynamics.

Catalyst particles in packed beds exhibit a variety of shapes yet are often assumed to be uniformly and homogeneously distributed. However, in practice, the packing arrangement is far from ideal and strongly influenced by particle, shape, orientation and the method of loading. The shape of catalyst particles plays a pivotal role in determining local voidage, flow distribution, and mass transfer characteristics in trickle bed reactors. Non-spherical geometries—such as trilobes or cylinders—introduce anisotropy and structural heterogeneities that significantly affect hydrodynamics, wetting efficiency, and catalyst utilization. These deviations from idealized assumptions challenge conventional reactor models and necessitate detailed investigation into how particle shape and packing influence the overall reactor performance.

This study investigates the influence of particle shape on packed bed structure and hydrodynamics, focusing specifically on trilobe catalyst particles. Bed configurations were characterized experimentally using high-resolution Micro-Computed Tomography (Micro-CT), while a simulation framework - Collision Guided Packing (CGP), was developed to model

the packing processes under several loading techniques. Structural metrics derived from both experimental and computational approaches enabled comparative analysis for trilobe and spherical particles.

Further, to evaluate the impact of bed structure on liquid distribution, flow behaviour was studied in randomly packed trilobe particles in a cylindrical bed under known feeding rates of air and water. The effects of multiple loading methods (central single-point, solid cone, hollow cone), superficial velocities, and axial bed positions were systematically examined. Fluid maldistribution was quantified using pressure drop measurements and the Maldistribution Index (M_f), based on spatial variations in outlet flow. To further elucidate the role of packing defects, a quasi-two-dimensional column was employed to enable direct visualization of flow paths. Controlled structural irregularities were introduced, characterized through mean dispersion metrics, and correlated with deviations in liquid spreading behaviour.

सारांश

ट्रिकल बेड रिएक्टर (TBR) गहन हाइड्रोप्रोसेसिंग के लिए एक अत्यंत महत्वपूर्ण उपकरण है, लेकिन इसकी कार्यक्षमता अक्सर हाइड्रोडायनामिक असफलताओं के कारण प्रभावित होती है, जिससे आधुनिक अल्ड्रा-लो सल्फर ईंधन मानकों के लिए आवश्यक लगभग 100% उत्प्रेरक (कैटेलिस्ट) उपयोग प्राप्त नहीं हो पाता। इस समस्या का मुख्य कारण यह है कि औद्योगिक स्तर पर TBR में जटिल गैर-गोलाकार (ट्राइलॉब) कैटेलिस्ट और अपूर्ण लोडिंग तकनीकों का उपयोग किया जाता है, जबकि वर्तमान डिजाइन मॉडल अभी भी समरूप (होमोजीनियस) बेड और आदर्श गोलाकार कणों की मान्यताओं पर आधारित हैं। यह शोध कार्य इस महत्वपूर्ण औद्योगिक चुनौती को संबोधित करते हुए कैटेलिस्ट की ज्यामितीय विशेषताओं और द्रव प्रवाह गतिकी के बीच बहु-स्तरीय संबंध स्थापित करने का प्रयास करता है।

पैकड बेड में कैटेलिस्ट कण विभिन्न आकृतियों में पाए जाते हैं, लेकिन प्रायः उन्हें समान और समरूप रूप से वितरित माना जाता है। जबकि वास्तविकता में, पैकिंग संरचना आदर्श नहीं होती और यह कणों के आकार, आकृति, अभिविन्यास (ओरिएंटेशन) तथा लोडिंग विधि पर निर्भर करती है। कैटेलिस्ट कणों का आकार स्थानीय रिक्तता (voidage), प्रवाह वितरण तथा द्रव्यमान स्थानांतरण विशेषताओं को प्रभावित करता है। ट्राइलॉब या बेलनाकार जैसे गैर-गोलाकार कण संरचनात्मक असमानता (heterogeneity) और अनैसोट्रोपी उत्पन्न करते हैं, जिससे हाइड्रोडायनामिक्स, वेटिंग दक्षता और कैटेलिस्ट उपयोग पर महत्वपूर्ण प्रभाव पड़ता है। ये प्रभाव पारंपरिक रिएक्टर मॉडलों की सीमाओं को उजागर करते हैं और विस्तृत अध्ययन की आवश्यकता को दर्शाते हैं।

इस अध्ययन में ट्राइलॉब कैटेलिस्ट कणों पर विशेष ध्यान देते हुए कण आकार के पैकड बेड संरचना और हाइड्रोडायनामिक्स पर प्रभाव का विश्लेषण किया गया है। बेड संरचना का प्रायोगिक विश्लेषण उच्च-रिज़ॉल्यूशन माइक्रो-कम्प्यूटेड टोमोग्राफी (Micro-CT) के माध्यम से किया गया, जबकि पैकिंग प्रक्रिया को मॉडल करने के लिए Collision Guided Packing (CGP) सिमुलेशन विकसित किया गया। प्रायोगिक और संगणकीय दोनों विधियों से प्राप्त संरचनात्मक मापदंडों के आधार पर ट्राइलॉब और गोलाकार कणों का तुलनात्मक विश्लेषण किया गया।

इसके अतिरिक्त, बेड संरचना का द्रव वितरण पर प्रभाव समझने के लिए बेलनाकार बेड में यादृच्छिक रूप से पैक किए गए ट्राइलॉब कणों के माध्यम से वायु और जल प्रवाह का अध्ययन किया गया। विभिन्न लोडिंग विधियों (केंद्रीय बिंदु, ठोस शंकु, खोखला शंकु), सतही वेगों तथा अक्षीय स्थितियों के प्रभाव का व्यवस्थित विश्लेषण किया गया। द्रव के असमान वितरण (maldistribution) को दाब ह्रास माप और आउटलेट प्रवाह के स्थानिक परिवर्तन पर आधारित मालडिस्ट्रिब्यूशन इंडेक्स (Mf) द्वारा मापा गया। पैकिंग दोषों की भूमिका को और स्पष्ट करने के लिए एक अर्ध-द्वि-आयामी कॉलम का उपयोग किया गया, जिससे प्रवाह पथों का प्रत्यक्ष अवलोकन संभव हुआ। नियंत्रित संरचनात्मक अनियमितताओं को उत्पन्न कर उन्हें औसत प्रसरण मापदंडों के माध्यम से विश्लेषित किया गया तथा द्रव प्रसार व्यवहार में होने वाले परिवर्तनों से संबंधित किया गया।

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