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Design and Characterization of Aerated Reactors Equipped with Coaxial Impellers

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Abstract

Aerated mixing vessels, traditionally employing single or multiple impellers on a shared shaft, are fundamental to gas-liquid contact operations across the chemical and biochemical industries. However, their efficacy in highly viscous Newtonian and non-Newtonian fluids is significantly hampered by inherent inefficiencies, leading to the formation of oxygen and nutrient-segregated regions within the reactor. Conventional gas-liquid mixers further exhibit drawbacks such as high power consumption, non-uniform shear rate distribution, and the presence of undesirable dead zones near vessel walls, all of which compromise overall mixing performance.

To overcome these critical limitations, this study introduces and thoroughly investigates a novel approach: an aerated coaxial mixing vessel. This configuration replaces traditional setups with a unique system featuring a central impeller and a wall-scraping anchor, designed to rotate at varying speeds and directions. In this advanced coaxial design, the anchor impeller, operating at a lower rotational speed, plays a crucial role in preventing the formation of the dead zones near the wall and efficiently directing the bulk fluid towards the central region. Concurrently, the central impeller, rotating at a higher speed, provides the necessary intense shear for effective gas dispersion throughout the fluid volume.

The primary objective of this comprehensive study was to systematically design and characterize the performance of these aerated coaxial reactors specifically for non-Newtonian biopolymer solutions. To achieve this, a meticulous assessment was conducted on the impact of several key parameters: the speed ratio (central impeller speed relative to anchor speed), rotating mode (co-rotating and counter-rotating configurations), central impeller type, fluid rheology (specifically using CMC solution, a pseudoplastic fluid, and xanthan gum solution, a pseudoplastic fluid exhibiting yield stress), and gas flow rate. The performance was evaluated across critical metrics including power consumption, gas holdup, bubble size distribution, and the volumetric mass transfer coefficient.

Beyond experimental characterization, this research also focused on developing robust predictive tools. Novel correlations for the Reynolds number and power number were meticulously proposed for this complex mixing system. To quantify gas holdup as a function of design and operating parameters, a non-invasive electrical resistance tomography (ERT) technique was successfully employed, and the collected data facilitated the development of new, accurate correlations for its estimation. Furthermore, the gas disengagement method, synergistically coupled with tomography, was utilized to precisely measure the bubble size distribution. The dynamic gassing-in method was also implemented to determine the mass transfer coefficient under various operating conditions, leading to the proposal of novel correlations for this crucial parameter. To further enhance predictive accuracy for both gas holdup and mass transfer, advanced machine learning techniques were successfully integrated and validated.

Complementing the experimental and empirical approaches, a sophisticated computational fluid dynamics (CFD) model, fully coupled with a population balance model (PBM), was developed to provide a fundamental understanding and simulation of the intricate hydrodynamics of gas dispersion within these non-Newtonian fluids.

This multi-faceted approach offers a significant advancement in the design and operation of aerated mixing systems for challenging pharmaceutical and biochemical applications.