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Computational Study of Turbulent Gas-Powder Mixture Flow in a Novel Pneumatic Hemostatic Delivery System

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Abstract

Upper gastrointestinal bleeding (UGIB) is a life-threatening condition affecting approximately 150 per 100,000 adults in Canada and 170 per 100,000 in the U.S., with mortality rates between 5% and 30%. Traditional treatments, including mechanical, thermal, and injection therapies, have limitations such as technical difficulty, reduced efficacy in hard-to-reach areas, and risks of tissue trauma. Hemostatic powders have emerged as promising alternatives, providing minimally invasive bleeding control. Among them, CounterFlow, a dry powder formulation containing calcium carbonate, thrombin, and tranexamic acid (TXA), enhances coagulation and stabilizes clots. However, its cohesive nature impairs flowability through narrow catheters, increasing the risk of clogging during endoscopic delivery.

To address this issue, a novel pneumatic conveying system inspired by cyclone-separator designs was developed for efficient CounterFlow powder delivery. The system comprises a cyclone mixing chamber, an oscillatory sieve, a pressure regulator, a solenoid valve, and an Arduino microcontroller. The cyclone chamber generates a strong swirling gas flow to mix and suspend the powder uniformly, while the oscillatory sieve prevents agglomeration and regulates the powder's mass flow rate. Computational fluid dynamics (CFD) simulations were conducted to analyze the turbulent flow dynamics and to improve the system's performance.

Using ANSYS Fluent, simulations modeled the gas-powder mixture flow through the cyclone device, with a time-dependent solver capturing the oscillatory sieve's motion. The discrete phase method (DPM) tracked powder particles, providing insights into suspension behavior, swirling flow, and pressure distribution. Key parameters, including sieve oscillation frequency and gas flow rate, were analyzed to enhance performance.

The results demonstrated that the swirling gas flow effectively suspends the powder, preventing sedimentation and reducing clogging risks near the cyclone outlet. However, potential clogging risks were identified, leading to iterative design refinements. Adjustments to the conical chamber geometry improved powder dispersion and reduced flow stagnation. These enhancements resulted in a final prototype capable of delivering CounterFlow powder with a stable and continuous flow suitable for clinical use.

This research highlights the critical role of numerical simulations in improvement of medical devices for hemostatic powder delivery. By addressing CounterFlow delivery challenges, this study contributes to safer and more effective endoscopic treatments for UGIB.