Design and Development of Electrospun Nanofiber Filter Media for Filtering Facepiece Respirators

by

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ABSTRACT

Conventional filtering facepiece respirators (FFRs) rely on electrostatically charged meltblown polypropylene filter media, whose dependence on electrostatic charging introduces limitations in manufacturing consistency, performance stability during use, compatibility with decontamination procedures, and material flexibility. These vulnerabilities, together with supply chain fragility and the environmental impact of single-use polypropylene, motivate the development of alternative filtration technologies. This thesis presents the systematic design, fabrication, and characterization of electrospun nanofiber filter media for FFR applications. By producing fibers with diameters approximately one order of magnitude smaller than those in meltblown filters, electrospinning yields filters that achieve high particulate filtration performance through purely mechanical collection mechanisms, without requiring electrostatic charging.

A design framework is developed that relates the structural characteristics of fibrous filter media — fiber diameter, solidity, and basis weight — to relevant performance targets for filtration efficiency and pressure drop. The framework rests on the expectation that the filtration performance of uncharged electrospun media is governed primarily by these structural parameters rather than polymer chemistry. This is first demonstrated with electrospun polyacrylonitrile (PAN) as a benchmark system, where materials meeting performance targets for National Institute for Occupational Safety and Health (NIOSH)-approved N95 FFRs are produced, and experimental measurements show quantitative agreement with slip flow-modified theoretical models for air resistance and filtration efficiency. The generality of the framework is then shown by extending it to two biodegradable polymers, polycaprolactone (PCL) and polylactic acid (PLA), from which electrospun materials meeting these targets are also produced.

Practical considerations for implementation, including adhesion of nanofiber layers to supporting substrates, removal of residual solvent, and enzymatic degradability of the biodegradable media, are also investigated. Prototype respirators fabricated from PAN and PCL media meet N95 criteria when tested using a NIOSH-specified automated filter tester, and translation of the PCL formulation to a continuous roll-to-roll electrospinning process yields extended rolls of filter media with uniform, N95 performance.

For the finest fibers studied, which deliver the best performance, Knudsen numbers extend into the transition regime where slip flow-corrected continuum models systematically underpredict permeability. To address this gap, two-dimensional direct simulation Monte Carlo (DSMC) simulations of gas flow through model nanofiber media are conducted across a wide range of fiber diameters and solidities, and a compact semi-empirical model for transition-regime permeability is developed that recovers the established models as limiting cases at low Knudsen number.

Collectively, this thesis demonstrates that electrospun nanofiber filter media can be rationally designed from a variety of polymers, including biodegradable materials, to meet respirator performance standards through mechanical filtration alone, and that the structure–performance relationships and modeling tools developed here provide a foundation for the continued design and scaling of nanofiber-based filtration technologies.

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