

**ADVANCING REALISTIC ASSESSMENT OF HVAC PARTICULATE
FILTER: TEMPORAL EVOLUTION IN FILTRATION AGING
PERFORMANCE, FAN ENERGY USE, AND IMPACT ON OCCUPANCY
RESPIRATORY EXPOSURE & CARCINOGENIC RISK**

by

Chunxu Huang

Lyles School of Civil and Construction Engineering

A Ph.D. Dissertation Abstract

People spend 90% of their time indoors, making indoor air quality a critical impactor of human health. Heating, ventilation, and air conditioning (HVAC) filters serve as the primary defense against fine and ultrafine particles (UFPs) entering mechanically ventilated buildings. However, evaluating their true performance is challenging, as current standardized testing protocols rely on coarse loading dusts that fail to represent real-world urban aerosols, and the long-term trade-offs between filter-induced energy penalties and human health benefits remain largely unquantified. This dissertation presents a comprehensive investigation into the long-term aging, in-situ performance evaluation, and health-economic trade-offs of HVAC filters.

First, a two-year in-situ evaluation of full-scale two-stage HVAC filter banks (MERV 8 pre-filters paired with MERV 8, 13, or 14 final filters) was conducted under continuous outdoor aerosol exposure. The study characterized the temporal evolution of size-resolved filtration efficiency, mass loading, pressure drop, and fan energy consumption, demonstrating that initial laboratory ratings are inadequate predictors of long-term, real-world service performance.

To bridge the gap between laboratory testing and in-situ performance, a novel rapid aging methodology was developed by integrating a thermal aerosol generator (TAG) into a full-scale HVAC test rig. The TAG reliably produced high-concentration, synthetic submicron potassium chloride (KCl) aerosols with particle size distributions closely mimicking those of real-world urban atmospheric aerosols, offering a significantly more representative loading medium than standard coarse dusts. This test rig was subsequently utilized to evaluate the effects of various operational and environmental conditions on filter loading dynamics. The findings revealed that higher volumetric airflow rates and lower relative humidity levels accelerate filter clogging, whereas aerosol feed rates minimally impact the dust-holding capacity, validating the methodology's robustness for accelerated, unbiased filter performance evaluations.

Finally, the dissertation developed an integrated techno-economic framework to quantify the health benefits and energy trade-offs of HVAC filtration. By coupling the two-year in-situ aerosol data with mass-balance and respiratory tract dosimetry modeling, the study assessed the UFP-induced Excess Lifetime Cancer Risk (ELCR) for building occupants. Additionally, an optimization approach is proposed to minimize filters' lifecycle cost by integrating the procurement cost and energy penalty. Collectively, a comprehensive cost-benefit analysis weighing lifecycle costs against the monetized Value of a Statistical Life (VSL) demonstrated that high-efficiency filters significantly reduce cancer risks and yield public health dividends that overwhelmingly offset their energy penalties, with the MERV 13 configuration emerging as the most economically balanced mitigation strategy.

In sum, this work advances the fundamental understanding of HVAC filter aging and provides rigorous methodologies and economic justifications for prioritizing high-efficiency filtration to protect public health in built environments.