Filter bypass affecting the performance of HVAC systems

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The filter-based Heating, Ventilation and Air-Conditioning (HVAC) systems are commonly used to remove aerosol particles indoors. The ASHRAE (1999) standard classifies filters according to their efficiency based on the performance of filter material, assuming that there is no bypass leakage. This assumption can be easily challenged given that a conventional HVAC filter housing assembly is not tight, which allows the aerosol particles to penetrate through a gap along the filter frame. Studies reported that this bypass flow can be significant, thus reducing the particle removal efficiency (Braun, 1986; Ottney, 1993; Stephens & Siegel, 2012).

In this effort, the effect of bypass leakage on the HVAC performance was investigated theoretically with a Computational Fluid Dynamics (CFD) model utilizing axisymmetric viscous flow equations in free fluid and porous zones, which were numerically solved by ANSYS FLUENT. Additionally, a full-scale experiment was conducted to measure the aerosol penetration size-selectively for different leak dimensions.

The total air flow rate, Q, through an HVAC filter system is a sum of the air flow rates through the filter media, Q_F, and the leakage, Q_L. The Total Inward Leakage, *TIL*, which quantifies of the overall efficiency of a filter assembly, is defined as the ratio of the particle concentration downstream of the filter layer, C, to the initial particle concentration, C_0, upstream:

$$TIL = \frac{C}{C_0} = \frac{Q_F P_F + Q_L P_L}{Q}$$

where P_F and P_L are the particle penetrations through the filter and leak, respectively. The *TIL* accounts for both particle fluxes: through the filter and the leakage.

For the numerical study, we chose a circular cross section with an area equal to the one of a typical HVAC filter, 20″×20″ (0.26 m^2). The permeability of a porous filter layer was obtained from the Darcy law as $k=Qh\mu/S_F\Delta p$, where h is the filter layer depth, μ is the air viscosity, and Δp is the pressure drop. For the MERV 11 grade filter with h=0.025 m, Q=0.41 m^3/s, and Δp=89 Pa, we found $k=7.83\times10^{-9}$ m^2.

The newly-developed model was deployed to simulate the fluid flow for different filter materials (determined by P_F) and different ratios of the leak area, S_L, to the filter area, S_F. The calculated *TIL* values are presented in Fig. 1 as a function of Δp for various S_L/S_F and P_F. For smaller leaks (S_L/S_F=0.1%), *TIL* is a constant entirely determined by the P_F value. As the leak size increases (e.g., to S_L/S_F=1%), *TIL* increases reflecting the bypass flow, and *TIL* becomes a non-linear function of Δp, which depends on the flow rate.

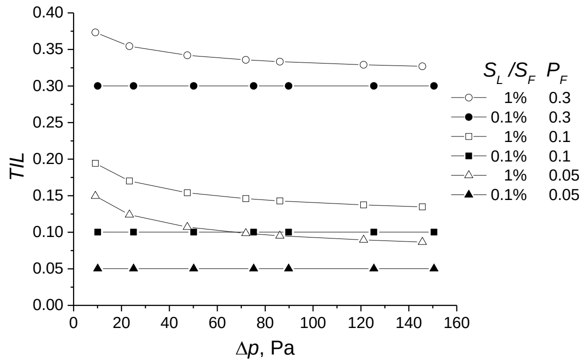

Figure 1. *TIL* as a function of Δp calculated for different S_L/S_F and P_F.

To experimentally verify the *TIL* values predicted by the model, a specially designed laboratory facility simulating an HVAC assembly was used. The NaCl aerosol was generated and measured upstream and downstream of a commercial 20″×20″ MERV 11 grade filter using a NanoID (Particle Measuring Systems, Boulder, CO, USA) and an ELPI (Dekati, Kangasala, Finland) operating in parallel. The tests were conducted at three S_L/S_F ratios: 0 (filter sealed, no external leak around the frame), 0.1 and 1%. It was found that the assembly with the smaller leakage (S_L/S_F = 0.1%) removed the particles almost as efficiently as the one with a perfectly sealed filter frame; however, the larger leakage (1%) significantly reduced the particle removal efficiency. These findings are consistent with the trends obtained with the CFD model. The tests also revealed that, in addition to the external leakage, there is an internal one caused by a poor seal between the filter material and the frame; eliminating the internal leakage decreased the particle penetration approximately twice.

The results of these theoretical and experimental studies suggest that the filter-based HVAC systems may be substantially enhanced by minimizing the bypass leakage as well as by improving the filter-to-frame seal.

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