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Development of a multi-functional HVAC facility for the evaluation of air cleaning technologies and ventilation performance

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Abstract Adequate ventilation with an effective airflow pattern and the air handling unit equipped with air purifier devices are common contaminant control methods for heating, ventilation, and air conditioning (HVAC) systems. Air cleaner purification performance, ventilation modes, and contaminant transportation need to be further explored to offer the safest indoor environment, especially under and post the COVID-19 pandemic. Therefore, this study developed a pilot-scale HVAC test rig to support various research initiatives. The setup was mainly composed of a square duct with the integration of an air filtration/purification testing system and 3 chambers with the ability to control the ventilation modes. The prequalification tests of the facility, including air leakage, velocity and aerosol uniformity, airflow and flow control verification tests, were conducted to show its feasibility. Results of the filter test were discussed as an example to show potential applications of the test rig. This paper can offer insights for future research about HVAC effectiveness.

Keywords; indoor air quality, HVAC, filtration, ventilation, experimental setup

I. INTRODUCTION

Modern life and workstyles encourage individuals to spend 90% of their time indoors [1]. Therefore, indoor pollution has attracted considerable attention, including particulate matter (PM), microorganisms, and volatile organic compounds (VOCs). During the COVID-19 pandemic, the promotion of indoor air quality (IAQ) has been identified as one of the most urgent environmental issues for public health. Heating, ventilation, and air conditioning (HVAC) systems could improve IAQ [1] by using the appropriate ventilation and effective filtration and air-cleaning technologies. However, there are several research gaps in the HVAC systems, such as filter applications, ventilation control and so on.

Installation of filters is one of the traditional filtration strategies in the HVAC system. Minimum efficiency reporting value (MERV) filters have been commonly used in HVAC systems in North America [2, 3]. In addition, several newly developed technologies, such as ultraviolet photocatalytic oxidation (UV-PCO) [4] and ultraviolet germicidal irradiation (UVGI) [5], are potential to be applied in the HVAC systems as well. However, these technologies still require further research on the optimization, operating conditions and effects on IAQ and so on.

In addition, ventilation in the HVAC systems plays a vital role in airborne contaminant control and thermal comfort for the indoor environment. Ventilation rate and airflow pattern are two key elements affecting airborne contaminants transport. Thus, the minimum ventilation rate or air change rate (ACH) is generally required in various building codes and standards for different built environments. For example, ASHRAE Standard 62.1 recommended the minimum ventilation rate requirement [6]. However, contaminant types, ventilation and filtration methods, and room structures are not specified, which leads to the effectiveness of ventilation on an airflow pattern remains uncertain.

Design and construction of the lab-scale experimental test rig is the first step for research related to the HVAC system. Therefore, a multi-functional pilot-scale HVAC setup was established in this study. The setup was composed of a square duct system connecting three chambers with different ventilation modes. Test rigs in the duct section were developed for testing various air cleaners. Design considerations, constructions, prequalification tests and one case study of practical applications were discussed, which offered references for developing a lab-scale HVAC system to support various research activities.

II. DESIGN CONSIDERATIONS AND DEVELOPMENT OF THE SETUP

The design of the setup referred to the actual ventilation system in a building. Firstly, the size of the setup was decided by considering the occupancy of the lab. There are three sizes of test rigs, including full-scale, pilot-scale, and bench-top sizes [7]. A full-scale setup was not considered because of the limitation of the space in the lab. On the other hand, a bench-top size fails to experiment with the ventilation mode exploration, and it is challenging to install several testing devices (e.g., UV lamps [7]) into a bench-top setup. Therefore, a pilot-scale duct system was designed. Besides, chambers were developed to fulfill the research requirement on ventilation in a building (Fig. 1).

The cross-sectional area (12.70×12.70 cm^2) of the duct was designed to allow the installation of all devices (e.g., fans, UV lights and filters) and sensors (e.g., the humidity/temperature sensor and flowmeters (F1-4)). Three chambers were constructed, and their volumes were 47.6 L (Chamber 1), 47.6 L (Chamber 2) and 28.3 L (Chamber 3), respectively. Designed chambers represented the size differences of rooms in a building. All chambers were connected to the square duct by the round ducts, in which 25 dampers and 2 flowmeters (F2 and F3) were installed to control the ventilation rate of the chambers. Because the location of the air diffuser and grille influenced transportation and accumulation of the pollutants (e.g., aerosols) [8], chamber 1 was designed with three ventilation modes, which enabled the airflow to go through the chamber from different directions.

To explore various filtration and purification technologies, two filtration/purification systems (F/P system 1 and 2) were integrated into the main duct system. F/P system 1, the supply air purification reactor, had 4 slots for the filter holder (2.54 cm width) with a 7.62 cm gap between the filters to install the UV light layers (3 UV lights for each layer), while F/P system 2, the return air purification reactor, had 1 filter slot and 2 UV light layers. Fig. 2 shows an example of installing a UV-PCO rector.

The setup should be operated under controllable conditions. From this perspective, a feedback control system was developed (Opto 22 control system) referring to the experimental condition of the HVAC system. The control system could record the airflow velocity, temperature, and relative humidity in various locations, and control the ventilation conditions in the pilot HVAC system by the three axial fans (velocity controllable), a humidifier, and a heater. Arrangements of components are shown in Fig. 2. Positions for components were designed referring to ASHRAE Standard 52.2 [2].

The distance from the aerosol injection point to the upstream air sampling section was only 50.8 cm, which was insufficient to allow for good mixing. Therefore, two cross-shaped sampling probes (labelled as 45° and 90° sampling tubes), a cross-shaped injection tube, and a mixing baffle were added (as shown in Fig. 2). Their designs are shown in Fig. 3. The tubes consisted of 20 holes of various diameters (5 holes per branch) on one side of the cross-tubes to ensure the airflow passing through each hole was the same. The mixing baffle had a 40% open area in its plate surface, in accordance with the design guidance of ASHRAE Standard 52.2 [2].

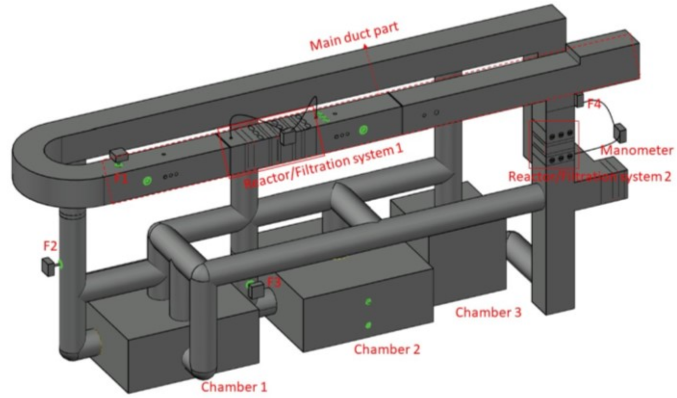

Figure 1 Design of the HVAC setup

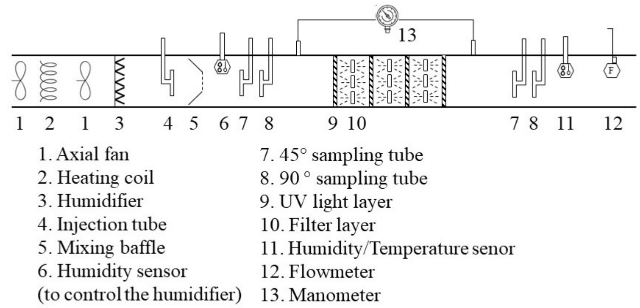

Figure 2 Components in the Main Duct of the HVAC Setup

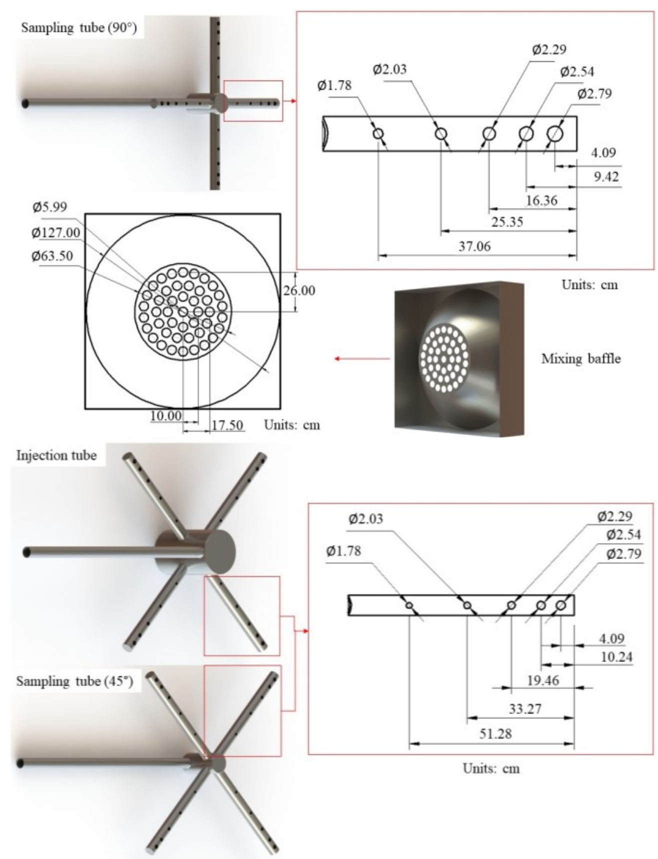

Figure 3 Designs of Components (units: cm)

III. PREQUALIFICATION TESTS

Apparatus prequalification tests of the main duct system have been conducted to quantitatively verify that the test rig could be used to test air filtration/purification technologies. One of the important applications of the constructed setup is to explore the filtration system installed into the HVAC system. From this perspective, aerosols, bioaerosols, and gaseous pollutants are regarded as target pollutants. To obtain the qualified results while feeding the above-mentioned pollutants into the setup, prequalification tests including leakage, aerosol uniformity, and velocity uniformity test were conducted. Besides, airflow verification and flow control verification were discussed to make sure the developed setup could be used in future research related to ventilation/transmission.

A. Leakage Test

Keeping leakage within an acceptable range is vital for quality control of the experiment and operator safety. Therefore, leakage of the main duct system connecting to the system outlet was assessed in this study.

Firstly, the maximum operating velocity and pressure drop were measured based on components installed inside the setup. Specifically, pressure drops of all components such as mixing baffle, prefilters, and HEPA filters were detected by a manometer (TSI/Alnor Model 5825) when installed into the F/P system 1.

Fig. 4 shows the diagram of the leakage test. All sensors and tubes were removed from the main duct, and all round-ducts were disconnected from the square duct part, leaving holes in the duct system. All holes, inlet and outlet of the duct system were sealed by aluminum foil and paperboards. In addition, the system was sealed by aluminum foil at the edge of the duct.

The compressed air was fed into the duct to keep the system under the targeted pressure. To reach the concentration uniformity of the tracer gas, the inlet and outlet of the duct were connected by a pump running at 28 L/min. Besides, the inlet and outlet of the Fourier transform infrared spectroscopy (FTIR iS50, Thermal Fisher Scientific) were connected to the setup. Thus, the whole system could be a closed-loop system.

Once the system reached the desired pressure by checking possible leaks, 2 μL pentane was injected into the system by a syringe. Concentrations of pentane in the duct system were analyzed by the FTIR while the gas samples were passing through it. Concentration decay was recorded by 40 mins to obtain the decay curve. Assuming the natural decay of pentane in the duct system is negligible, the leakage airflow (Q_{leak}) and leakage ratio (R_L) could be obtained by the following equations,

$$C = C_0 \times e^{-\frac{Q_{leak}}{V}\times t} \quad (1)$$

$$R_L = \frac{Q_{leak}}{Q_{Max.}} \times 100\% \quad (2)$$

where C_0 is the initial concentration (ppm), C is the concentration (ppm) at time t (min), and V is the duct volume (110.6 L). $Q_{Max.}$ is the maximum operating flowrate (1.30 m^3/min) of the developed setup.

B. Air Velocity Uniformity test

Testing velocity uniformity ensures that the concentration of the sampling point is representative of the entire cross-section. The uniformity of the challenge air velocity across the duct cross-section was determined by a nine-point traverse (Fig. 5) in the main duct immediately upstream of the F/P system 1 at round 0.5 m/s, 0.73 m/s and 0.9 m/s. Average velocity at 1 min at each point was detected by a velocity sensor (Series AVPT, Dwyer).

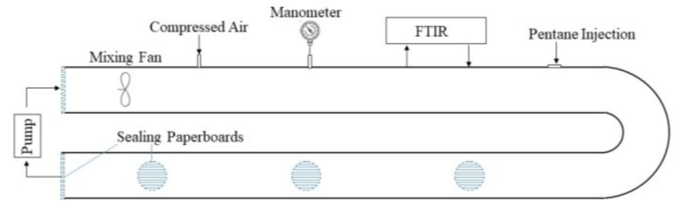

Figure 4 Diagram of the leakage test

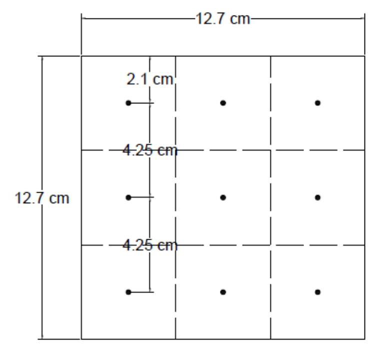

Figure 5 Nine-point traverse testing of the velocity uniformity

C. Capability to Conduct the Aerosol-Related Experiment

Considering one of the potential research activities is to test aerosol removal efficiencies, aerosol uniformity was conducted to explore the setup's capability on filter evaluation [2]. KCl aerosols were generated by a particle generation system composed of compressed air, a Collison nebulizer (1 Jet, CH Technologies, USA), a Kr-85 charge neutralizer (Model 3077A, TSI Inc., USA), and a diffusion dryer (Silikagel, DDU 570, TOPAS), which was connected to the injection tube. In addition, an optical particle sizer (OPS Model 3330, TSI Inc., USA) was used to detect concentrations of particles with sizes from 0.3 μm to 10.0 μm as referring to ASHRAE Standard 52.2 [2].

The 45° and 90° sampling tubes were installed in the upstream and downstream sampling positions, respectively. The aerosol uniformity was determined by measuring concentration differences of 45° and 90° sampling probes at 0.6 m/s, 1.0 m/s and 1.35 m/s duct velocity.

D. Airflow Verification

In this study, flowmeters (Model AT400, KANOMAX Inc., USA) composed of an anemometer and a transmitter were used in the developed system, designed to detect airflow of large duct systems. Considering the non-uniform distribution of the air velocity in the small duct system, the feasibility of using these flowmeters should be verified.

In this experiment, toluene was injected into the system from the injection tube by a speed controllable syringe pump (Fisher Scientific Inc.). Adsorbent tubes (TO-17, Agilent Technologies, Inc) connecting to sampling pumps (GilAir3, Sensidyne Inc.) at 50 ml/min were used to collect samples in the upstream and downstream sampling point of the duct, which were analyzed by Thermal Desorption Gas Chromatography-Mass Spectrometry (Agilent) to obtain the actual concentration of toluene in the duct system. The theoretical concentration of toluene can be calculated based on the injection amount, which could be used to calculate practical airflow of the duct further. Airflow readings of F1 at 100%, 75%, and 40% of speed for fan 1 and fan 2 were recorded. The airflow of the duct system could be verified by comparing differences of the calculated airflow and reading of F1.

E. *Flow Control Verification*

As studies on ventilation and contaminate transmission are expected to be explored by the developed HVAC test rig, airflow entering chambers should be controllable. Airflow passing through chambers was controlled by adjusting dampers. There were 4 motorized dampers (D1-4), and 21 ON/OFF dampers (e.g., D5) installed into the duct system (Fig. 6).

The airflow distribution into chambers 1 and chamber 2 can be controlled by adjusting the opening degree of motorized dampers D1 and D2 with D3 closed. At this condition, the airflow rate in the main duct was recorded by F1 (Fig. 1), while the airflow rate for chambers 1 and 2 was recorded by F2 and F3.

F. *Case study on filtration test*

Commercial MERV 6, MERV 8, MERV 11 and MERV 13 filters were purchased from Canadian retail stores during the COVID-19 pandemic. Each filter was cut into a square and installed into a 12.70×12.70×2.54 cm filter holder whose edges were sealed by tape. Aerosol injection and sampling systems were connected to injection and sampling probes, respectively, to detect the removal efficiency of the particles at the size of 0.3-1.0 μm. The particle generation system was composed of compressed air, a Collison nebulizer (1 Jet, CH Technologies, USA), a Kr-85 charge neutralizer (Model 3077A, TSI Inc., USA), and a diffusion dryer (Silikagel, DDU 570, TOPAS). In addition, 20% KCl (20 g of KCl to 100 ml of ultrapure water) was used as the source of salt PM. An optical particle sizer (OPS Model 3330, TSI Inc., USA) was used to detect particles with diameters in the range of 0.3-1.0 μm and with channel sizes of 0.30-0.40, 0.40-0.55, 0.55-0.70, 0.70-1.00 μm, through which size-resolved analysis was performed.

Filters were assessed by following the test procedure of ASHRAE Standard 52.2 [2]. In specific, aerosol concentrations were detected alternately by the OPS at upstream (4 samples) and downstream (3 samples) sampling points while the aerosol fed into the duct system. The removal efficiency (E) of filters at various particle size were obtained by Eq. (3) and Eq. (4).

$$E = \left(1 - \frac{\text{downstream particle concentration}}{\text{upstream particle concentraiton}}\right) \times 100 = (1 - \frac{P_o}{R}) \times 100 \quad (3)$$

$$P_o = \frac{\sum_{i=1 \to n} P_{i,o}}{n} = (\sum_{i=1 \to n} \frac{D_{i,o,t} - D_b}{U_{i,e,t} - U_b})/n \quad (4)$$

where, $U_{i,e,t}$ is the estimated upstream concentration, which is calculated by taking the average of two upstream measurements recorded before and after the downstream measurements ($D_{i,o,t}$). the correlation ratio (R) was the ratio of downstream to upstream particle counts without the filter installed in the test duct, equal to P_0 without a filter [2]. D_b and U_b are the average background counts before and after the penetration test at the downstream and upstream sampling points, respectively, and n is the number of samples.

IV. Results and Discussion

A. *Results of the Leakage Test*

The maximum pressure drop due to the installation of the components is mainly from filters and a mixing baffle in the system. The largest pressure drop requirement is for bio-aerosol-related experiments. According to ASHRAE Standard 185.1 [9], setups used in the bio-experiments should include at least two HEPA filters (as pre- and final- filters), one mixing baffle, which at the maximum operation flowrate (1.30 m^3/min), have 340 Pa and 160 Pa pressure drop in this study. With the consideration of the pressure drop for tested filters or purification devices, the largest pressure drop requirement in the single-pass mode was decided as 600 Pa.

Fig. 7 shows decay curves of the pentane concentration under the duct pressure of 600 Pa (E1) and 652 Pa (E2). According to Eq. (1) and Eq. (2), R_L for E1 and E2 was 0.88% and 0.94%, respectively, which was within the leakage ratio (<1.0%) of ASHRAE Standard 52.2 [2].

B. *Aerosol Uniformity and Velocity Uniformity Test*

We used two types of sampling tubes to explore the aerosol uniformity of the developed system (Table 1). Differences at each aerosol size were smaller than 15% [2], except for aerosols larger than 7.0 μm. This is because the aerosol concentration in the duct was lower than 10 p/cm^3 which cannot be detected steadily. In conclusion, the main duct system can be used on filtration evaluation for particles with the size of 0.3-5.5 μm.

The uniformity of the air velocity for the duct cross-section was determined by a nine-point traverse in the main duct system at three different velocities. The coefficient of variation (CV) of air velocity values at the nine corresponding grid points (7.7±0.4%) was less than 10% at each airflow rate. The result meets the requirement of ASHRAE Standard 52.2 [2].

C. *Airflow Verification*

Fig. 8 shows the differences between the readings of F1 and the calculated airflow in the duct system. The calculated flow rate and reading of F1 are linearly dependent (R^2=0.9923), and their differences are smaller than 10%. This result indicates that the anemometer-based flowmeter could be used in the developed pilot-scale duct system.

D. Flow-control Verification

For a flow-controllable system, total flow readings of F2 and F3 were similar to that for F1 as shown in Fig. 9. As a result, the flow entering chamber 1 and chamber 2 can be controlled by adjusting dampers. Airflow entering chamber 3 was not verified in this study. Airflow of chamber 3 can be calculated by (F1-F2-F3) when the leakage test of the whole system was verified.

E. Results of the Case study on Filtration Test

Once the prequalification tests passed, the developed setup was used to evaluate the removal efficiencies of various filters, as shown in Fig. 10. As a result, MERV 13 filter could reach > 60% removal efficiency for 0.3-1.0 μm particles, while removal efficiencies of the MERV 11 filter were 34% - 58%. MERV 6 and MERV 8 filters had a relatively limited performance on the removal of 0.3-1.0 μm particles. The experiments about MERV filter evaluation showed one of the potential applications of the constructed test rig on the exploration of filtration systems in the building.

V. CONCLUSION

A multi-functional HVAC experimental setup was established. The developed main duct section could be used to test various filtration and purification technologies, while three chambers with various airflow patterns will serve all ventilation experiments with controllable airflow rates by dampers. Prequalification tests of the main duct system, including leakage, aerosol uniformity and velocity uniformity tests, airflow and flow control verification, were discussed. A case study of MERV filter testing demonstrated the capability of the test rig in filtration applications. Consequently, the developed experimental setup can fulfil the requirements of various research objectives.

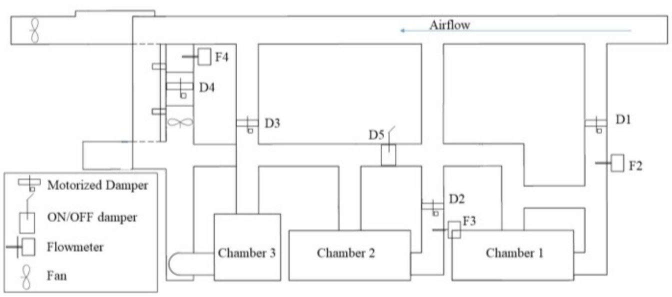

Figure 6 Diagram of the Flow-control Experiment

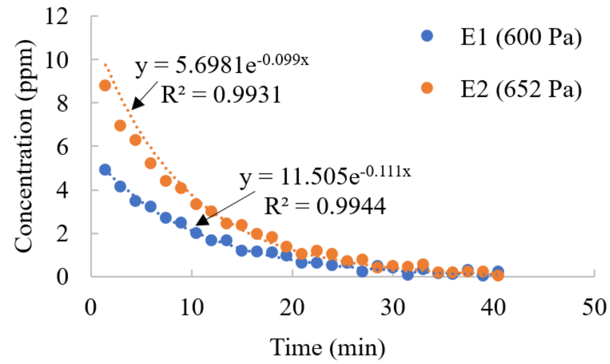

Figure 7 Pentane Decay Curves on the Leakage Test

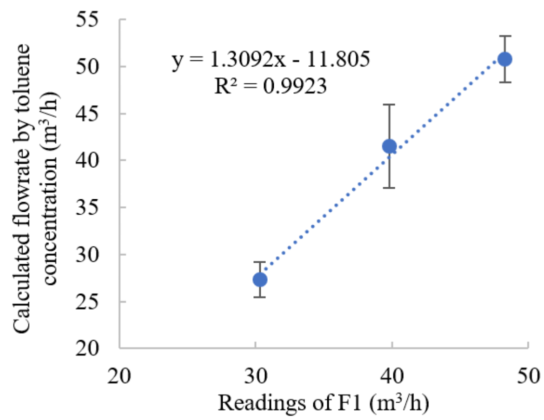

Figure 8 Relationship of calculated airflow rate and the reading of F1

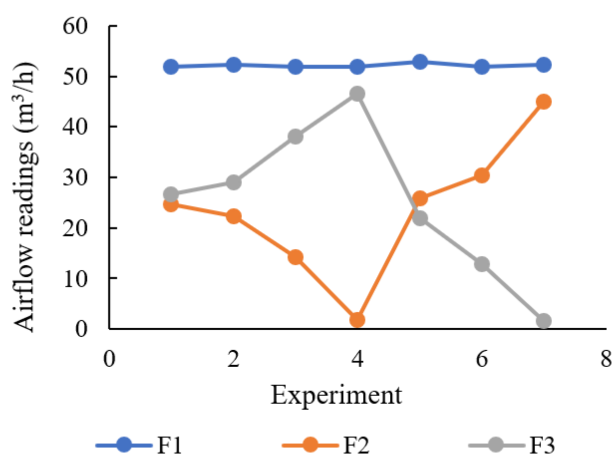

Figure 9 Airflow readings in the main duct (F1) and branches (F2 and F3)

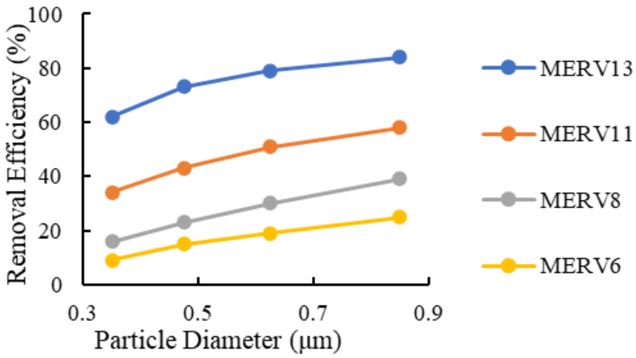

Figure 10 Removal efficiencies of MERV filters

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Table 1 Aerosol concentration differences between two sampling points in the duct system

	Aerosol diameter range (µm)											
Velocity (m/s)	*0.3-0.4*	*0.4-0.55*	*0.55-0.7*	*0.7-1.0*	*1.0-1.3*	*1.3-1.6*	*1.6-2.2*	*2.2-3.0*	*3.0-4.0*	*4.0-5.5*	*5.5-7.0*	*7.0-10.0*
1.35	2%	2%	4%	5%	5%	7%	2%	3%	8%	7%	4%	32%
1.0	1%	3%	1%	1%	1%	5%	4%	7%	9%	10%	1%	18%
0.6	3%	4%	5%	4%	4%	6%	6%	5%	8%	10%	4%	20%