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Development of a Novel Bench-scale Setup for Evaluation of In-duct Air Filters Against Simulated Wildfire Smoke

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Executive Summary

Wildfire smoke can pose a significant hazard to human health, mainly due to its composition and prolonged exposure. Although wildfires are local events, wildfire smoke disperses horizontally and vertically in the atmosphere and could be transported a long distance form the point of origin. As a result, the impact of wildfires extends far beyond their physical footprint, putting a large population at risk. Induct air filters are the most commonly used method to maintain a habitable indoor air quality during wildfire smoke seasons, however, the standard test for evaluating their performance uses an aerosol of salt which is different from smoke composition.

In this report, the development of a bench-scale setup for testing the performance of the in-duct air filters exposed to simulated wildfire smoke is presented. The setup consists of a tube furnace to generate the simulated smoke and a chamber to house the filter and the instrumentation. Pine needles and wood chips were used in a tube furnace at oxidative pyrolysis conditions to produce the smoke. The setup showed reproducible production of smoke and thorough mixing of particulate matter (PM) in the chamber. This setup could be used to evaluate the short term and long-term performance of in-duct air filters.

1 Introduction

Wildfires occur more frequently in Canada and around the world as global warming leads to more frequent heatwaves. Wildfire smoke can spread across large territories in fine particles and creates serious health threats. For example, in the summer of 2021, the British Columbia heatwave led to wildfires in Canada West [1], which spread to eastern Canada as far as New Brunswick [2]. The main emissions negatively affecting the air quality are fine and coarse particulate matter (PM), carbon monoxide (CO), methane (CH4), nitrous oxide (N2O), nitrogen oxides (NOx), volatile organic carbon (VOC) in addition to many other air toxics.

In order to maintain a habitable indoor air quality (IAQ) during wildfire smoke seasons, induct air filters are commonly used to filter PM. According to ASHRAE 52.2 “Method of testing general ventilation air cleaning devices for removal efficiency by particle size” [3] , in-duct filters are rated following a performance test comparing concentrations of particles, sized between 0.3 and 10 µm, upstream and downstream of the filter and given a Minimum Efficiency Reporting Value (MERV) rating. The particles in the test are basically an aerosol of potassium chloride (KCl) produced using a laboratory aerosol generator. However, the structure and composition of a combustion aerosols, present in wildfire smoke, are different from a KCl aerosol.

The development of a new bench-scale setup used for testing induct air filters exposed to simulated wildfire smoke is presented in the following sections. In order to achieve a through mixing of the smoke, preliminary numerical modelling was conducted to optimize the design of the setup. Instrumentation used for measuring the concentration of PM were verified by comparing the results with a highly accurate particle sizer (TSI Inc. Aerodynamic Particle Size Model 3321). The reproducibility of smoke generation in the setup and mixing of PM at filter upstream were also verified.

2 Mixing Chamber CFD Modelling

Numerical simulations were conducted using the Fire Dynamic Simulator (FDS) [4] to optimize the design of the mixing chamber. FDS is an open-source Computational Fluid Dynamic (CFD) code. FDS is widely used for fire simulations. FDS employs Large Eddy Simulation (LES) to model turbulence.

The setup consisted of two parts;

(1) tube furnace for smoke generation, and
(2) mixing chamber to house the filter and the instrumentation.

The main purpose of the modelling was to optimize the size of the openings in the chamber providing the make-up air without disturbing the air flow on the filter surface. In addition, results from modelling were used to evaluate the mixing at the filter upstream.

A domain of sizes 85 cm×85 cm×60 cm was created in FDS and a box of dimensions 65 cm×65 cm×40 cm was built to simulate the air flow in the mixing chamber from the tube furnace outlet to the surface of the filter. The mesh size was 1 cm in x, y and z directions. The outlet of the tube furnace was modeled as a burner generating smoke and the filter surface was modeled as a suction vent of volumetric flow rate of 0.4 m^3/s.

Three configurations were considered and simulated. The first configuration used 2 openings on each of the top, left and right sides of the chamber with dimensions 55 cm×5 cm, 5 cm×30 cm and 5 cm×30 cm, respectively. The second configuration used 3 windows on each of the left and right sides with dimensions 5 cm×30 cm each. Finally, the flow in the first configuration was regulated using a screen which was modelled as a 2D array of particles to account for the flow drag. Schematic views of the three configurations are presented in Figure 1.

The velocity contours from the simulation results were averaged over 200 s and are shown in Figure 2. The velocity contour appears to be more uniform in the second configuration. Therefore, it was chosen in fabrication of the mixing chamber.

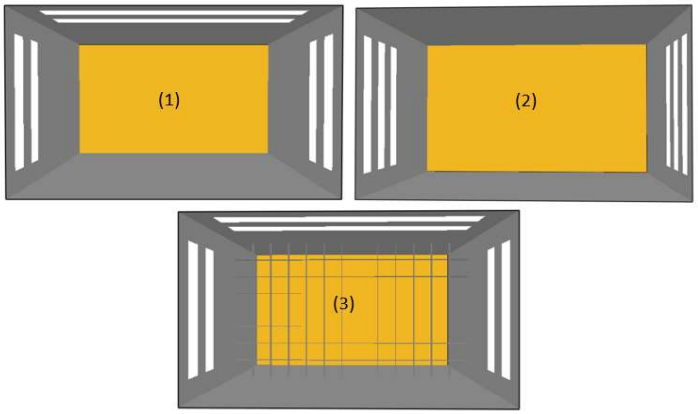


Figure 1. Different configuration of inlet air vents considered in the simulations. The yellow surface represents the simulated surface of the filter.

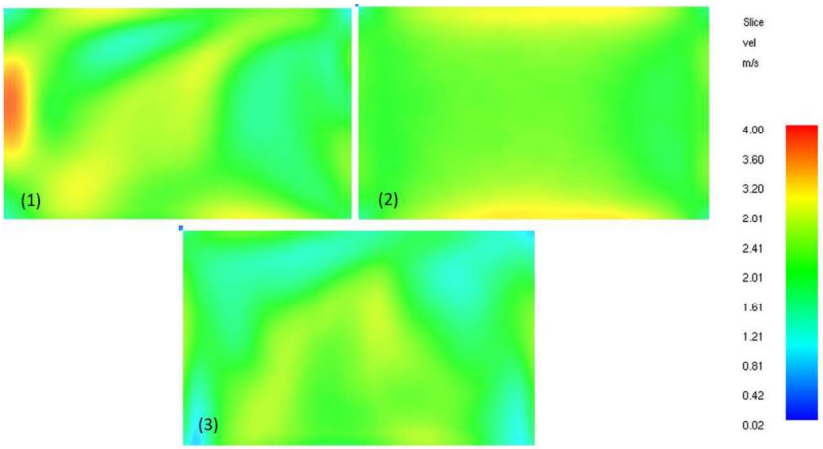


Figure 2. Velocity contours (m/s) from simulating the 3 different potential inlet configurations of the mixing chamber (1) openings at top and sides (2) openings at sides (3) openings on top and sides and a screen

3 Experimental Procedures

3.1 setup

The required setup serves two purposes: (1) generate simulated wildfire smoke, and (2) house the filtering media and instrumentation to evaluate the filtration efficiency. Figure 3 shows a photo of the developed setup which consists of 2 parts; tube furnace and a mixing chamber. Details about each part are provided in the following subsections.

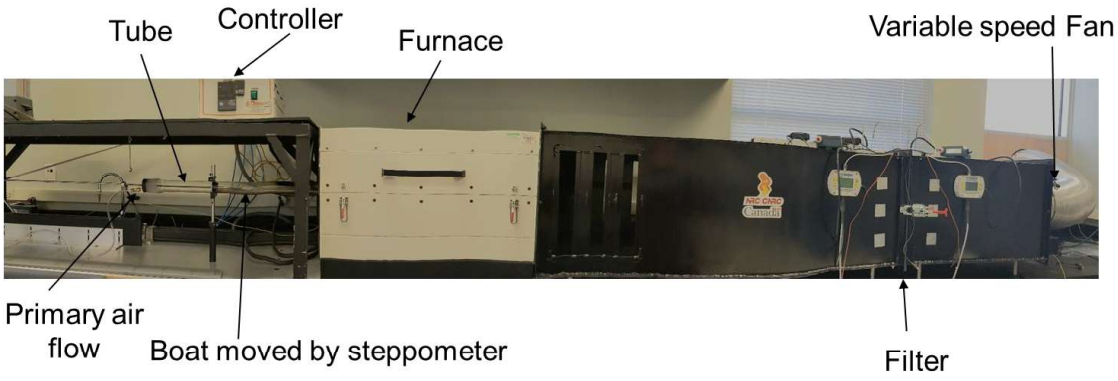


Figure 3. The components of the experimental setup.

3.1.1 Tube furnace

Tube furnace is widely used in characterizing toxic products since the device allows to replicate the generation of toxic products under different combustion conditions. It is generally used to achieve the following burning conditions: oxidative pyrolysis, well-ventilated flaming, small vitiated fires in closed or poorly ventilated compartments, and post flashover fires in open compartments. These different conditions can be achieved by adjusting the furnace temperature and the equivalence ratio (i.e., ratio between the mass of combustible material and primary air flow). It consists of;

1- A furnace with a controller to adjust the heating temperature. The furnace had a heating zone of length 0.6 m and diameter of around 0.06.
2- A quartz tube which was sealed from one end with a piece of cork and had an inlet for primary airflow. The tube was 1.6 m long. The primary airflow was controlled using a rotameter (Omega FM-1051B-V-E100) to match the required value.
3- A quartz boat on which the sample was placed and automatically moved in the tube using a stepper driver. The length of the boat was 0.8 m.

The tube furnace was used in our set-up to generate the simulated wildfire smoke. Tube furnaces have been used by many researchers to determine the PM produced from burning different materials under different fire conditions [5–9]. Recently, Goo [10] used a tube furnace to investigate the size distribution of PM from burning wood pellets. The tube furnace is also suitable for reproducible and repeatable routine measurements of fire gaseous effluents. Purser et al. [11] investigated the repeatability and reproducibility of the steady state tube furnace. They tested 4 polymers in 3 different laboratories under 2 combustion conditions and reported consistent results with satisfactory agreement. Similar work was conducted by Stec et al. [12]. Moreover, Stec et al. [13] characterized the tube furnace for assessing the fire toxicity and reported its efficacy to model the production of fire toxic gases in repeatable and reproducible manner.

In order to generate simulated wildfire smoke; pine needles and wood chips were burnt in the tube furnace. Pine needles were chosen as a source of smoke since they cover the forest floors and highly flammable because of presence of turpentine oil in them and even a spark and high temperature can lead to ignition of these needles. In addition, wildfire propagation through surface fire is very common. Dried pine needles were collected and conditioned at 24°C and 40% RH. Untreated Wood chips were selected because they have similar composition as pine needles and can be obtained from commercial stores.

During wildfires, there is simultaneous smouldering and flaming combustion; but most of the emissions (PM and VOCs) are produced from smouldering [14]. Therefore, oxidative pyrolysis conditions were applied to generate the simulated wildfire smoke in the tests. Table 1 shows the experimental conditions.

Table 1. Experimental conditions for generation of simulated smoke

Sample material	Pine needles/ wood chips
Sample mass	5 g
Sample length	200 mm
Sample distribution	25 mg/mm
Conditioning temperature	24°C
Conditioning humidity	40% RH
Boat feed rate	40 mm/min
Primary airflow	0.66 L/min
Furnace temperature	350°C

3.1.2 Mixing Chamber

The mixing chamber was designed to (1) mix the smoke produced from the tube furnace before passing through the filter, (2) house the filter, (3) house the instrumentation for pre- and post-filter measurements. It was built from steel with dimensions of 190.5 cm (L) × 63.5 cm (W) × 40.6 cm (H) (75”× 25”×16”). Following the modelling results, the chamber had 3 windows on each side with dimensions 30.5 cm (H) × 5.1 cm (W) (12”× 2”) each to provide the makeup air. The chamber was air tight and had a groove of width 2.5 cm (1”) to house the filter. A variable speed fan of maximum flow of 0.503 m3/s (1065 CFM) was located at the end of the chamber to provide the required flow. The filter was placed at 127 cm (50”) from the furnace.

3.2 Measurements

Wildland fires generate massive emissions into the atmosphere over a short period of time and increase local and distant concentrations of PM. Emissions from wildfires are physically and chemically complex. The main emissions, negatively affecting the air quality include PM and gaseous emissions (carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), volatile organic carbon (VOC)). Details about these emissions and their emission factors can be found in [15].

3.2.1 Measuring PM

The concentration of PM was measured using Nanozen DustCount 9000 devices, which are Optical Particle Counters (OPC) that provide real-time particle count, particle size distribution and mass concentration data. The devices were tested against TSI Inc. Aerodynamic Particle Sizer (APS) (Model 3321).

The test was conducted using an aerosol of aqueous sodium chloride 0.9% by mass solution. A TSI 8026 was used as the aerosol generator, the mode particle diameter was 700 nm. The instruments were connected to a customized mixing system to ensure the same particle concentrations were sampled by all instruments. The system was placed in a test room, salt particles were dosed and then allowed to decay. This method allowed a direct comparison of instrument response over a wide range of particle sizes and concentrations. It further checked instrument response times to concentration changes. This is essential when using more than one particle counter to measure particles in a comparative manner such as a filtration study.

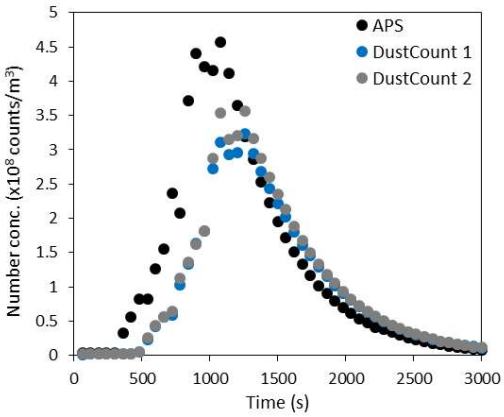


Figure 4. Number concentration profiles as measured by APS and the 2 nanozens.

Dosing was conducted for 1080 s then the PM concentration started to decay in the room. The number concentration profiles measured by the APS and the two nanozens are presented in Figure 4. It can be seen that the nanozen profiles coincided, however some data points deviated from the APS values. This deviation can be clearly seen during the dosing phase and at concentrations higher than 3.2×10^8 counts/m^3. This can be attributed to the fact that the nanozens reached their saturation limit at this value.

The number concentration profiles of different size ranges as measured by APS and Dustcount can be seen in Figure 7. Particles are classified into 3 bins according to their diameter;

- E1: particles with a diameter between 0.3 and 1 μm
- E2: particles with a diameter between 1 and 3 μm
- E3: particles with a diameter between 3 and 10 μm

It can be seen that the APS and nanozen measurements for E1 and E2 are in very good agreement. However, there is a big deviation in E3 measurements from both devices.

When comparing the measured concentrations from the devices during only the decay phase and after neglecting concentrations higher than 3.2×10^8 counts/m^3 (where the nanozens and APS mismatch), the nanozens showed a very good agreement with the APS with R-squared > 0.99 (refer to Figure *6*).

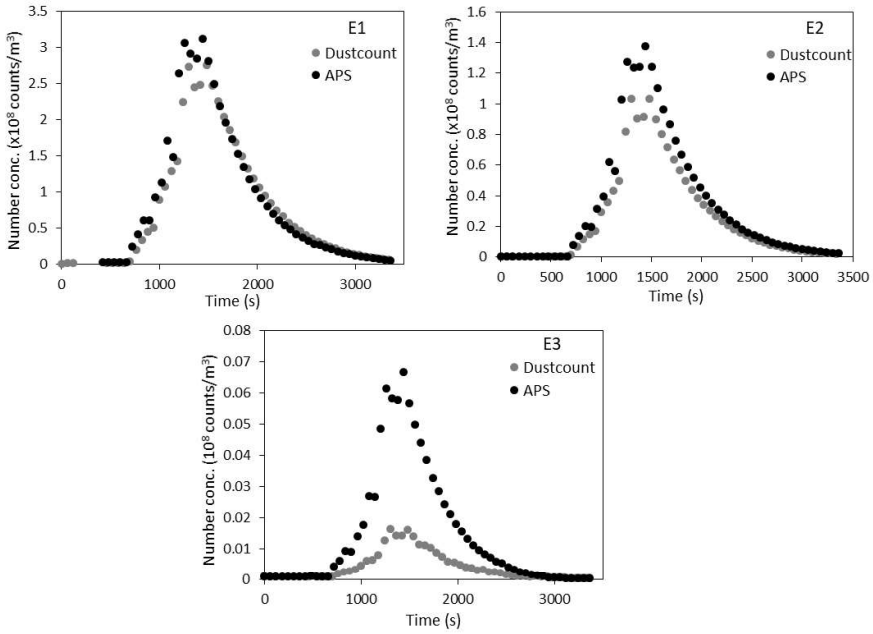


Figure 5. Comparison of different particle size ranges (E1, E2 and E3) as measured by APS and Dustcount

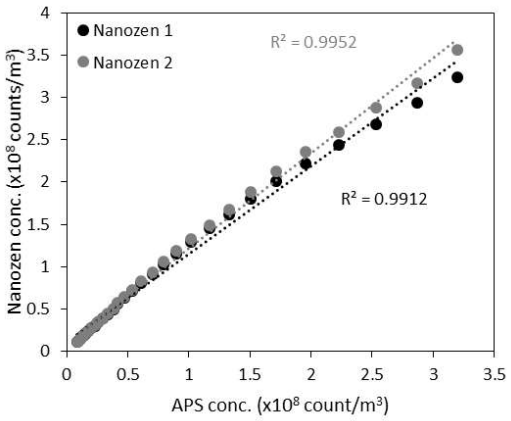


Figure 6. Number concentrations measured by the APS and Dustcounts (nanozens) during the decay phase

Since the main goal of our study was to investigate the filtration efficiency by comparing the PM concentrations at filter upstream and downstream using the two nanozens, it was more important to compare the nanozens against each other.

Figure 7 compares the number concentrations from the two nanozens and it shows excellent agreement between both devices. However, the linear regression equation displayed on the figure was used to correct the concentrations from nanozen 1 in all the presented figures and efficiency calculations.

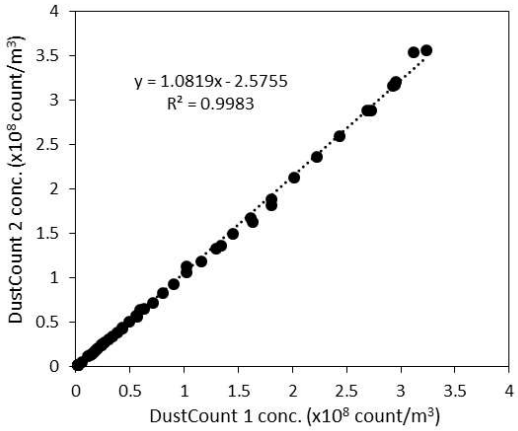


Figure 7. Number concentrations from the two nanozens.

3.2.2 Measuring Gaseous Emissions

Recent studies at the British Columbia Center for Disease Control (BCCDC) show that the hazard from wildfire $PM_{2.5}$ is higher than that from regular $PM_{2.5}$, which might be attributed to the interaction between wildfire VOC and $PM_{2.5}$ [16]. A better understanding of these interactions and comparing the composition of anthropogenic and wildfire VOCs would contribute to mitigating the health impact of wildfire smoke.

Gaseous emissions concentration measurements were made by Fourier transform infrared spectroscopy (FTIR) using a MKS MultiGas 2030. However, negligible amounts of chemicals were detected when 5 g of material were burned. The mass of the burning material was increased till carbon dioxide, carbon monoxide, methane, 1,2,3-trimethylbenzene, formaldehyde and methanol were detected when 50 g of material were burned. The concentrations were lower than the short- and long-term exposure limits stated by Health Canada for residential indoor air quality [17]. Only formaldehyde showed a concentration of 1.37 ppm which is higher than its exposure limits (short (1 hr): 0.1ppm, long (24 hrs): 0.04). The results are tabulated in Table 2.

Table 2. Chemical compounds produced at oxidative pyrolysis condition from different mass and type of burning material balance at 350°C

Burning material & mass	Chemical compound	Max. measured concentration (ppm)	initial detection of FTIR (ppm)	Permissible exposure limit (PEL)
15g – pine needles	CO_2	485	460	5000
	CO	3.90	0.60	50
	CH_4	2.26	1.96	1000
	H_2O	5950	5600	N/A
50g- pine needles	CO_2	507	460	5000
	CO	8.75	0.60	50
	CH_4	3.10	0.40	1000
	H_2O	5548.3	4285	N/A
	CH_3OH***	1.20	1.02	200
	$C_6H_3(CH_3)_3$ *	3.86	0.66	25
50g – wood chips	CO_2	494.70	464.9	5000
	CO	8.13	0.40	50
	CH_4	3.42	0.38	1000
	CH_3OH	1.39	0.38	200
	CH_2O**	1.37	0.64	0.75
	H_2O	2282.50	2140	N/A

*$C_6H_3(CH_3)_3$: 1,2,3-Trimethylbenzene | **CH_2O: Formaldehyde | ***CH_3OH: Methanol

However, the concentration of PM from 50 g of burning material was beyond the maximum detection limit of the Nanozen DustCount 9000. In addition, most of the in-duct air filters are rated based on their efficiency of filtering PM of different sizes and only filters with activated carbon are the primary approach for gaseous emissions. As health data is primarily related to exposure to $PM_{2.5}$ from wildfire smoke [16], that was the focus of our study.

3.3 Procedures

In each experiment, five grams of pine needles or wood chips were uniformly distributed on the boat at 2.5 mg/mm over 200 mm. The boat was automatically fed into the furnace at 40 mm/min using linear actuator driven by P70360-PNN stepper drive. Before each run, the fan speed was adjusted to achieve an air velocity of 1.2-1.25 m/s on the filter surface based on traverse measurements made over a 9-point equal-area grid as recommended by ASHRAE standard 52.2 [3] .The conditions of the tube furnace were set at the required values presented in section 3.1. The dustcounts were turned on and the test started when the stepper starts driving the boat into the furnace.

4 Results and Discussion

In this section, the results from testing the reproducibility of smoke generation and mixing in the chamber are presented. It should be noted that the results from testing induct air filters are not presented in this report.

4.1 Setup Reproducibility

Figure 8 shows the average mass and number concentrations of PM produced during different runs from burning pine needles at the conditions prescribed in section 3.1.1. The figure shows that similar PM concentration was measured for each of the three runs presented. Similar behaviour was also seen when burning wood chips as seen in Figure 9. Therefore, it can be concluded that similar PM concentration can be produced from the tube furnace under the same operating conditions.

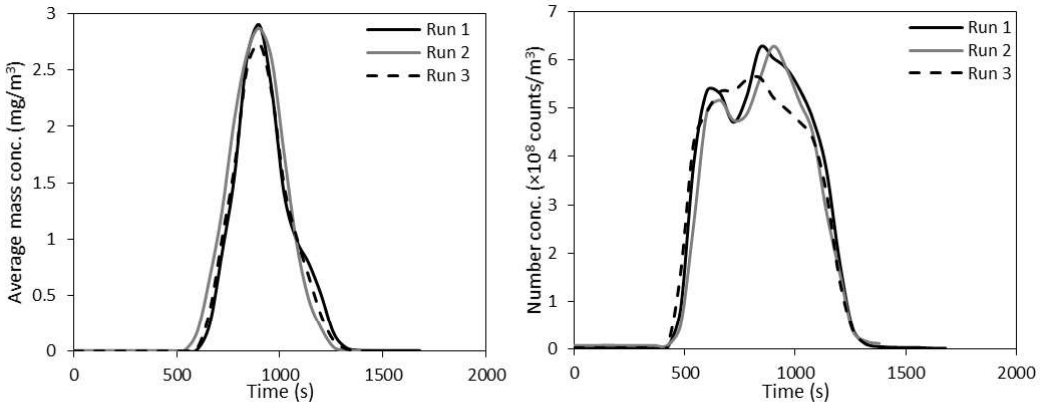


Figure 8. Average mass (left panel) and number (right panel) concentrations at filter upstream for pine needles.

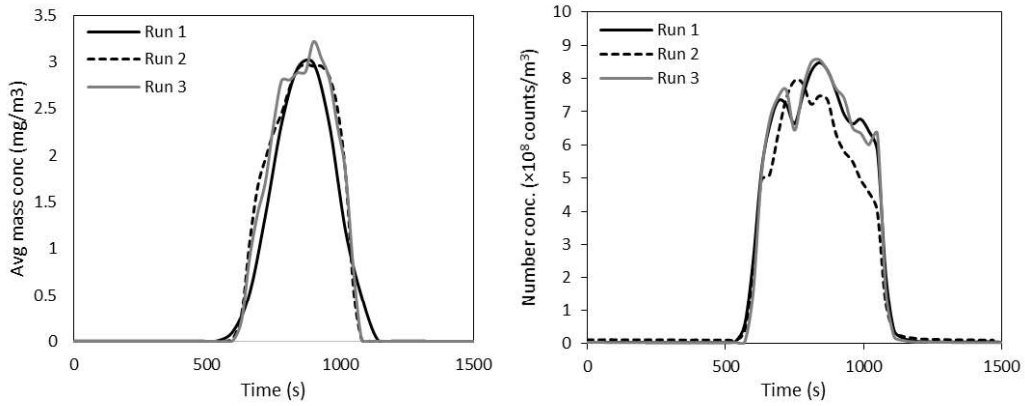


Figure 9. Average mass (left panel) and number (right panel) concentrations at filter upstream for wood chips

Concentrations of PM at the filter upstream and downstream without placing the filter were also checked. Figure 10 shows that the PM profiles at both locations are the same in the absence of the filter. Therefore, any reduction in the PM concentration during the conducted filtration tests was attributed to the filter.

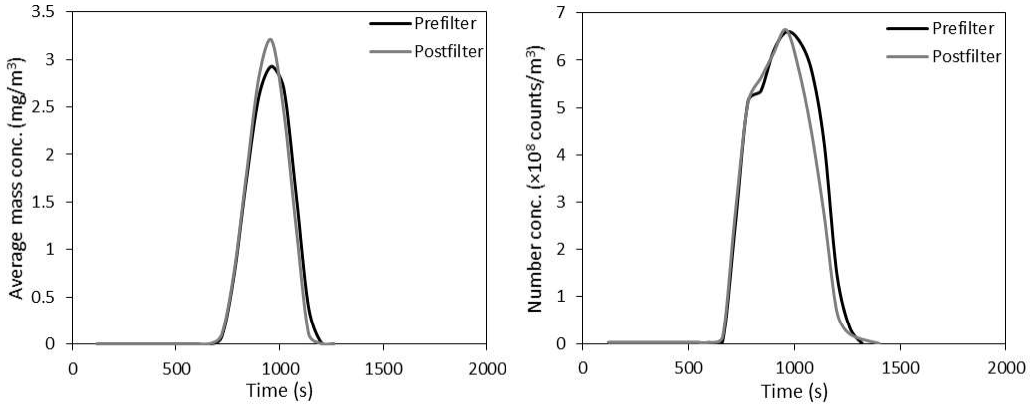


Figure 10. Average mass (left panel) and number (right panel) concentrations at the location of the filter upstream and downstream without placing the filter

4.2 Mixing in the chamber

The concentration of PM resulting from burning pine needles according to the conditions in Table 1 was measured at different locations at filter upstream. The results and the locations are presented in

Figure **11**. The concentration of PM at the sampling location during filtration testing is also presented on the same figure. It can be seen that the concentration profiles were almost the same for locations 1,2,4,5,7, however, higher concentrations were seen at locations 3 and 6. The average and maximum standard deviations between the runs is 0.1 and 0.62 respectively. Generally, there is relatively good agreement between the concentrations at all the locations which means that there is good mixing of PM at the filter upstream. This was also confirmed by the numerical simulations. The velocity profiles at the filter upstream shown in **Figure 2**-2 shows a nearly uniform velocity profile and consequently good mixing of PM.

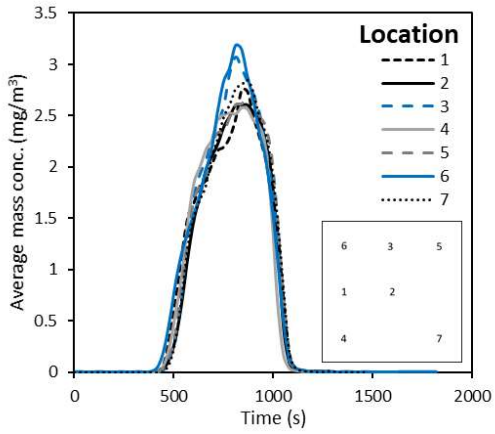


Figure 11. Average mass conc. of PM at different locations at filter upstream. The inset represents a schematic of the different locations on the filter

The PM concentration profiles at the filter downstream and different locations are presented in **Figure 12**.

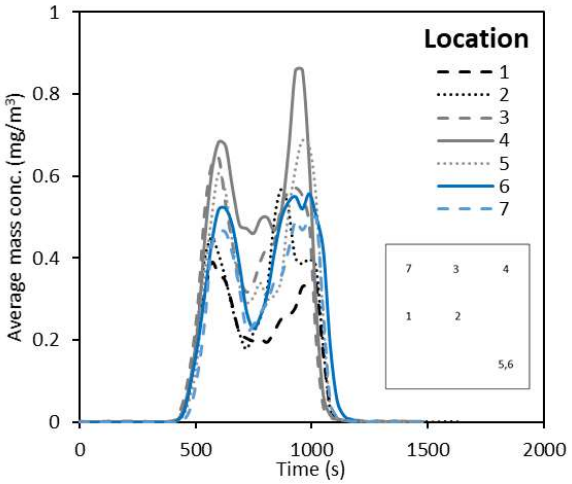
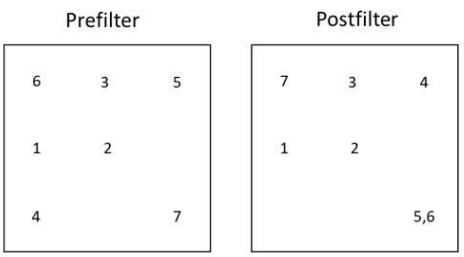


Figure 12. Average mass conc. of PM at different locations at filter downstream. The inset represents a schematic of the different locations on the filter

Since the main goal of the setup is to evaluate the filtration efficiency, PM concentrations were measured at different upstream and downstream locations using an induct air filter. The sampling locations at filter upstream and downstream for each run are shown in Figure 13. The locations varied between both upstream and downstream samplings are at same location (runs 1, 2 and 3) or totally opposite locations (runs 4, 6 and 7).



Run	PM number filtration efficiency (%)
1	52
2	53
3	50
4	40
5	42
6	45
7	45

Figure 13. Different locations of sampling at filter upstream and downstream

The number filtration efficiency from each run is also shown in Figure 13. It can be concluded that the highest efficiency was seen when both sampling locations were the same (runs 1,2 and 3). The lowest efficiency was seen in run 4 where both sampling locations were totally opposite. In all our tests, both sampling locations at filter upstream and downstream were the same and at the centre of the filter.

5 Conclusions and Future Work

The development of a bench-scale setup for testing the performance of in-duct air filters against simulated wildfire smoke was presented. A tube furnace was used to generate the simulated smoke and a chamber was built to house the filter and instrumentation. To generate smoke, pine needles and wood chips were subjected to oxidative pyrolysis conditions by burning them in a tube furnace. The setup showed reproducible production of smoke and well-mixing of PM in the chamber. The next step will be using the setup in evaluating induct air filters with different MERV ratings to verify their performance for smoke particulate matter removal.

References

[1] J. Winter, Deadly British Columbia heatwave sows wildfires across Canada's west, (n.d.). Deadly British Columbia heatwave sows wildfires across Canada's west.

[2] Satellite images show wildfire smoke spreading across Canada, (n.d.). https://globalnews.ca/news/8042760/air-quality-environment-canada-wildfires/.

[3] ASHRAE. Standard 52.2-2017. Method of testing general ventilation air cleaning devices for removal efficiency by particle size, in. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. Atlanta., (2017).

[4] K.B. McGrattan, R.J. McDermott, C.G. Weinschenk, G.P. Forney, Fire dynamics simulator, technical reference guide, 2013.

[5] T.R. Hull, J.M. Carman, D.A. Purser, Prediction of CO evolution from small-scale polymer fires, Polym. Int. 49 (2000) 1259–1265.

[6] J. Rhodes, C. Smith, A.A. Stec, Characterisation of soot particulates from fire retarded and nanocomposite materials, and their toxicological impact, Polym. Degrad. Stab. 96 (2011) 277–284.

[7] A.A. Stec, J. Readman, P. Blomqvist, D. Gylestam, D. Karlsson, D. Wojtalewicz, B.Z. Dlugogorski, Analysis of toxic effluents released from PVC carpet under different fire conditions, Chemosphere. 90 (2013) 65–71.

[8] P. Blomqvist, T. Hertzberg, H. Tuovinen, K. Arrhenius, L. Rosell, Detailed determination of smoke gas contents using a small-scale controlled equivalence ratio tube furnace method, Fire Mater. Int. J. 31 (2007) 495–521.

[9] T. Hertzberg, P. Blomqvist, Particles from fires—a screening of common materials found in buildings, Fire Mater. 27 (2003) 295–314.

[10] J. Goo, Study on the real-time size distribution of smoke particles for each fire stage by using a steady-state tube furnace method, Fire Saf. J. 78 (2015) 96–101. https://doi.org/10.1016/j.firesaf.2015.08.008.

[11] J.A. Purser, D.A. Purser, A.A. Stec, C. Moffatt, T.R. Hull, J.Z. Su, M. Bijloos, P. Blomqvist, Repeatability and reproducibility of the ISO/TS 19700 steady state tube furnace, Fire Saf. J. 55 (2013) 22–34. https://doi.org/10.1016/j.firesaf.2012.10.002.

[12] A. Stec, T.R. Hull, J. Purser, P. Blomqvist, K. Lebek, A comparison of toxic product yields obtained from five laboratories using the steady state tube furnace (ISO TS 19700), Fire Saf. Sci. 9 (2008) 653–664.

[13] A.A. Stec, T.R. Hull, K. Lebek, Characterisation of the steady state tube furnace (ISO TS 19700) for fire toxicity assessment, Polym. Degrad. Stab. 93 (2008) 2058–2065. https://doi.org/10.1016/j.polymdegradstab.2008.02.020.

[14] J. Reid, R. Koppmann, T. Eck, D. Eleuterio, A review of biomass burning emissions part II: intensive physical properties of biomass burning particles, Atmospheric Chem. Phys. 5 (2005) 799–825.

[15] N. Elsagan, M. Adelzadeh, Air Treatment Technologies for Shelter-in-place Scenarios in Response to WUI Fires, 2020.

[16] C.J. Matz, M. Egyed, G. Xi, J. Racine, R. Pavlovic, R. Rittmaster, S.B. Henderson, D.M. Stieb, Health impact analysis of PM2.5 from wildfire smoke in Canada (2013–2015, 2017–2018), Sci. Total Environ. 725 (2020) 138506. https://doi.org/10.1016/j.scitotenv.2020.138506.

[17] Health Canada, Residential indoor air quality guidelines., (2020). https://www.canada.ca/en/health-canada/services/air-quality/residential-indoor-air-quality-guidelines.html.

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