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Field-based Inter-comparison of an Indigenously Designed and Developed off-centric $PM_{2.5}$ Impactor with a Standardized Impactor

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A R T I C L E I N F O

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A B S T R A C T

Inertial impactors can segregate particles based on their inertia difference, although it is associated with an inherent problem of particle bounce-off, which yields errors in the particle collection. Previously we have developed a novel $PM_{2.5}$ impactor with an off-centric rotating nozzle which has less tendency of particle bounce-off. In this study, we have evaluated the performance of this off-centric impactor by comparing it with a conventional impactor having the same flow rate and same cut-off diameter ($PM_{2.5}$, 15 LPM and sampling time: 24 h) through two sets of experiments. In experiment 1, the off-centric impactor was not rotated, and thus, it mimics like a conventional impactor. In experiment 2, the off-centric impactor was rotated to 90 degrees after each 6 h. For each set of experiments, we gravimetrically compared the filter substrate and the impaction surface from both the impactors. In experiment 2, the off-centric impactor exhibited a higher difference in the collected mass and greater impaction area than that in experiment 1, which is attributable to the reduction of particle bounce-off. We performed FE-SEM (Field Emission-Scanning Electron Microscope) analysis on the aerosol laden filters, which confirms the cut-off diameter of the novel off-centric to be $PM_{2.5}$.

1. Introduction

Air pollution research is indispensable for fighting against air pollution, a severe global threat [Honda et al., 2017; Wang et al., 2018; Zhou et al., 2018; Locosselli et al., 2019]. Air sampling is the first and foremost step in air pollution research. In off-line PM air sampling technique, size-specific collection of representative PM is obligatory to estimate the genuine health risk associated with PM pollution. Because, small particulates, only below a specific size range (i.e. $PM_{2.5}$), can enter into human lungs and causes various health issues and even premature deaths **[**Caiazzo et al., 2013; Chowdhury and Dey, 2016; Maji et al., 2018**].**

Inertial impactors are the key component of impaction based off-line PM air samplers and segregate particles based on their inertia difference. They are age-old, simple devices, works on impaction theory and are famous for their reasonably good particle collection efficiency [Marple and Willeke, 1976; McFarland et al., 1978; Chen and Huang, 2016]. Pouchet developed the first impactor in 1860. Over time, many researchers have designed and developed several types of impactors [Marple et al., 1991; Demokritou et al., 2002a, 2002b, 2002c, Marple 2004; Furuuchi et al., 2010]. Inertial impactors are till date widely used by researchers from various fields [Vinchurkar et al., 2009; Furuuchi et al., 2010; Mehdizadeh et al., 2017; García-Ruiz et al., 2019]. However, like any other instrument, inertial impactors also have some limitations. Particle bounce-off is one of the inherent problems associated with inertial impactors which perturbs the inlet flow and incurs errors in the estimation [Rao and Whitby, 1978a, 1978b]. This phenomenon is more pronounced when pollution loading is high, or sampling is prolonged for a long duration [Turner and Hering, 1987]. In order to get more accurate results, many researchers have performed significant research to reduce the problem of particle bounce-off and developed different impactors like particle trap impactor, virtual impactor and experimented with various impaction surfaces [Biswas and Flagan, 1988; Lee and Kim, 2002, 2003; Lim and Lee, 2006]. However, even in recent years, inertial impactors are the most commonly used for size segregated collection of particles. Research has revealed that even though oil-coated impaction plates can lessen the tendency of particle bounce-off, it still happens when for prolonged sampling duration [Chen and Huang, 2016]. Previously several researches were pursued on laboratory and field-based inter-comparisons to evaluate the performance of newer PM measurement techniques against the conventional inertial based sampling techniques [MacIntosh et al., 2002; Kim et al., 2004]. Researchers have used gravimetric, Field Emission-Scanning Electron Microscope (FESEM) and chemical analysis for quantification and characterization of the collected particulates [Ayers et al., 1999; Jones et al., 2006; Price et al., 2010; Buonanno et al., 2011; Okuda et al., 2015; Ivey et al., 2017].

Earlier, a single-stage $PM_{2.5}$ inertial impactor was developed and validated in our laboratory following standard protocol against USEPA recognized instruments [Gupta et al., 2011]. Furthermore, recently, another

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single-stage $PM_{2.5}$ impactor was designed and developed in our laboratory with a reduced level of particle bounce-off [Biswas and Gupta, 2017]. This novel design has a rotatable off-centric nozzle and a mechanism to revolve the nozzle plate to a specific angle with respect to the stationary impaction plate. This mechanism provides a fresh impaction surface upon each rotation. Therefore, by distributing the total particle loading (higher than the designed cut-off diameter) into multiple points, or in other words by providing more impaction area, the tendency of particle bounce-off is reduced.

In this study, we have examined the performance of this novel off-centric impactor by comparing it with the conventional single-stage $PM_{2.5}$ impactor previously designed and developed from our laboratory [Gupta et al., 2011]. Briefly, we have deployed both the impactor samplers on the terrace of CESE (Centre for Environmental Science & Engineering) building in the premises of Indian Institute of Technology Kanpur (India). We performed co-located field sampling using the same type of filter substrate (quartz in this study). After the sampling, we retrieved the aerosol laden filters from both the impactor samplers and performed the gravimetric comparison. Furthermore, we have examined the physical diameter of the collected particles on the filter substrates in FESEM analysis for confirming the cut-off diameter of the new off-centric impactor.

2. Methodology

For assessing the performance of the novel off-centric $PM_{2.5}$ impactor, we decided to operate it for sample collection simultaneously with a collocated conventional $PM_{2.5}$ impactor previously developed in our laboratory [Gupta et al., 2011]. The previous design was licensed and commercialized by Envirotech, a leading air sampler manufacturer company in India (Envirotech). Both the impactors are single-stage inertial impactor have the cut-off diameter of $PM_{2.5}$ and operate at 15 LPM. We have strategically conducted two different sets of experiments. In the first set of the experiment (hereinafter referred to as experiment 1), both the co-located impactors were operated simultaneously for 24 h, and the off-centric impactor was not rotated for the entire sampling duration. Thus, it acted as a conventional impactor but with an off-centric nozzle. However, in the second set of the experiment (hereinafter referred to as experiment 2), total run-time of both collocated impactors was kept 24 h, but the off-centric impactor nozzle was rotated 90 degrees after every 6 h period. Both the experiments were performed for 4 days each.

Quartz filters (47 mm in diameter) were used for these experiments. As per standardized protocol, the filters were conditioned prior to PM sampling. Filter substrates were initially heated up to 450 °C temperature in a muffle furnace for 8 h. Then the filters were placed in a desiccator partially filled with activated silica gel to remove any moisture content in it while cooling down. After 24 h the filters were carefully kept inside individual butter paper, labelled adequately for easy identification and were kept safe in a zip lock bag. Subsequently, the filters were equilibrated for ~ 12 h under controlled temperature (24 °C) and RH (~35 %). The gravimetric weight of the empty filter material was carefully measured on an analytical microbalance (Mettler Toledo; model no. MSU 6.6-000) post to the static charge neutralization. Plastic forceps were used to hold the filters from their peripheral region to avoid contamination and possible mishandling damage of any kind. After weighing, the filters were again preserved in their respective butter paper pouches and finally kept in the zip lock bag.

Aerosol sampling for both experiments 1 and 2 were conducted on the terrace of CESE building, IIT Kanpur. Two individual air suction pumps were used for the two impactor assembly. The flow rates of both the impactors were individually set to 15 LPM using two rotameters. Each rotameter was calibrated against a highly precise mass flow controller. The impaction surfaces of both the impactors were routinely cleaned and prepared with high-density silicone grease. The initial weights of the impaction plates loaded with impaction grease were measured with a microbalance. After sampling, we carefully retrieved the filters from both the impactors and their final weights were measured in a similar manner as aforementioned. After sampling, we also measured the gravimetric weights of the impaction plates having particles absorbed on it. Subsequently, we measured the impaction surface with a Dino-Lite digital microscope (model AD-413T) and the area of the impaction spots. Afterwards, we assessed the physical size of collected particles on the filters by performing Field Emission-Scanning Electron Microscope (FE-SEM) (model no. NOVA NANOSEM 450) analysis on the particle-laden filter papers.

3. Results and Discussion

It was observed from the experiments that the impaction spots on the individual impaction plate had a darker zone around the center of the spot which indicates higher concentrations of particles collected in the central region. However, the outer region of the same spot was relatively lighter, and thus, could have less concentration of particles. Areas of both the darker and lighter zone were tentatively measured with Dino-Lite digital microscope.

3.1 First set of experiment

For the first set of the experiment, both the impactors produced a single impaction spot as the off-centric impactor was kept un-rotated throughout the sampling period. In this case, the off-centric impactor behaved more like a conventional impactor but with an off-centric placement of the nozzle. After sampling, both the impaction plates were weighed, and from the difference of their final and initial weights, the mass of the captured particles (higher than the cut-off diameter, $PM_{2.5}$) on the impaction surface was calculated and compared between the two impactors. The gravimetric analysis revealed a negligible difference in the accumulated mass (Table 1, Wilcoxon-Mann-Whitney Test, p-value = 0.7).

The impaction spots were observed under the Dino-Lite digital microscope, and their areas were approximately estimated as discussed. The difference in the area was not huge and arose plausibly due to the difference in the design of the impactor samplers (Table 2, Figure 1). Another reason might be the approximate selection of the area of the impaction spot. However, the objective of this experiment was not to precisely measure the impaction locations but to observe and compare them in magnified views.

Table 1 Difference in final and initial weight of impaction plate for both impactors in experiment1.

Sample ID	Difference in final and initial weight of impaction plate for off-centric impactor (mg)	Difference in final and initial weight of impaction plate for conventional impactor (mg)	Variation (%)
Ex1 (Day 1)	3.578	3.504	2.06
Ex1 (Day 2)	3.249	3.167	2.52
Ex1 (Day 3)	3.102	3.035	2.16
Ex1(Day 4)	2.956	2.877	2.67

Table 2: Comparison of impaction spot areas of the off-centric and conventional impactor in experiment 1.

Off centric impactor impaction spot		Conventional impactor impaction spot	
Total area (mm^2)	Central area (mm^2)	Total area (mm^2)	Central area (mm^2)
52.437	27.605	63.222	20.270
Outer radius (mm)	Inner radius (mm)	Outer radius (mm)	Inner radius (mm)
4.085	2.964	4.486	2.540

The difference between the final and initial weights of the filter is a gravimetric representation of the captured target sized particles (here $PM_{2.5}$). The weight difference of the filters (simultaneous collection) retrieved from both the impactors was measured and found to be statistically similar (Table 3, Wilcoxon-Mann-Whitney Test, p-value =

Table 3: Difference in final and initial weight of the filter substrate for both impactors in experiment 1.

Sample ID	Difference in final and initial weight of filter paper for off-centric impactor (mg)	Difference in final and initial weight of filter paper for conventional impactor (mg)	Variation (%)
Ex1 (Day 1)	2.379	2.357	0.9
Ex1 (Day 2)	1.657	1.644	0.8
Ex1 (Day 3)	1.573	1.544	1.1
Ex1(Day 4)	1.421	1.408	0.9

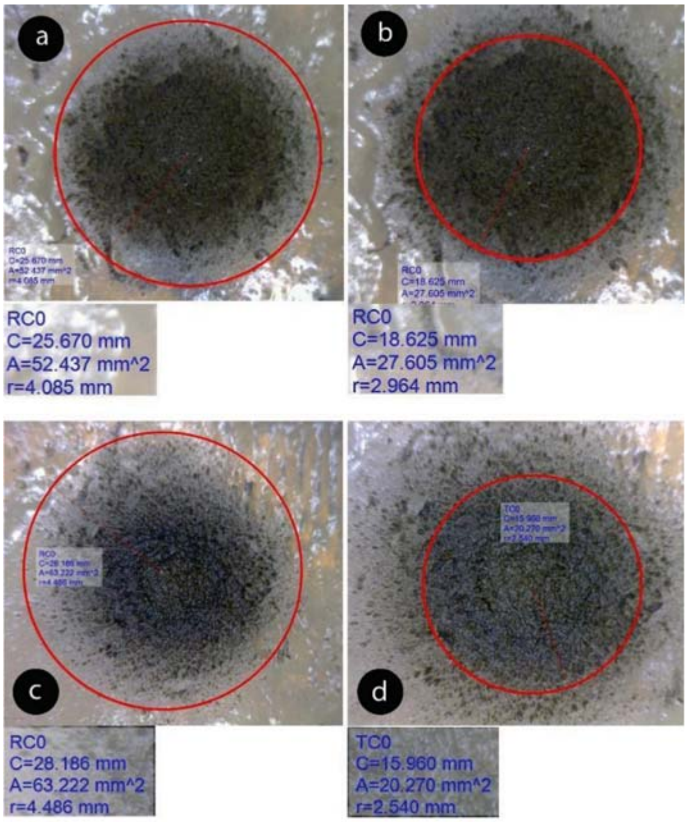

Figure 1. Area estimation of the impaction spots from experiment 1. Above figures showing: a. total area as predicted for off-centric impactor impaction plate, b. area near the central region as predicted for off-centric impactor impaction plate, c. total area as predicted for conventional impactor impaction plate, d. area near the central region as predicted for conventional impactor impaction plate.

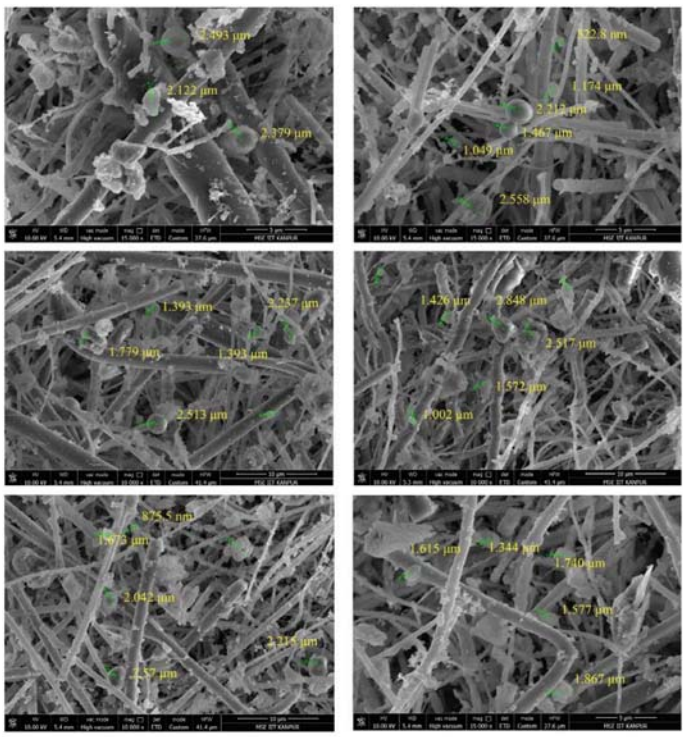

Figure 2. Field Emission-Scanning Electron Microscope (FE-SEM) analysis of aerosol laden filter retrieved in experiment 1 from off-centric impactor.

0.69). This partially confirms that while keeping the impaction nozzle un-rotated, the collection behavior and performance of this novel off-centric impactor are the same as compared to its conventional symmetric model.

Afterwards, FE-SEM analysis was performed on filters retrieved from both impactors to practically assess the physical size (diameter) of the captured particles on the filters. For every filter, FE-SEM analysis has been done on multiple filter portions to overcome/minimize any observational biases. The analysis showed that both the filters were loaded with $PM_{2.5}$ particles as particles larger than 2.5 microns were not found in both the cases (Figure 2). This confirms that the newly designed off-centric impactor sampler satisfies its fundamental characteristics of $PM_{2.5}$ collection.

3.2 Second set of experiment

In experiment 2, the off-centric impactor was rotated to 90° after each successive 6 h sampling interval for a total sampling period of 24h (on one filter substrate). Similar types of analyses were performed as conducted under experiment 1. On weighing impaction plates, it revealed that the percentage variation in weight between the two impaction plates in experiment 2 (~ 4.5%) as compared to that observed in experiment 1 (~ 2.5%) was not very huge but statistically significantly higher (by 2%) (Table 4, Figure 3, Wilcoxon-Mann-Whitney Test, p-value < 0.05). This might be because of the improved collection efficiency at the impaction surface due to the plausible reduction of particle bounce-off owing to utilization of larger impaction area as the off-centric impactor was rotated thrice during the total sampling period.

Table 4: Difference in final and initial weight of impaction plate for both impactors in experiment 2.

Sample ID	Difference in final and initial weight of impaction plate for off-centric impactor (mg)	Difference in final and initial weight of impaction plate for conventional impactor (mg)	Variation (%)
Ex2 (Day 5)	2.846	2.718	4.5
Ex2 (Day 6)	2.649	2.526	4.6
Ex2 (Day 7)	2.602	2.481	4.7
Ex2 (Day 8)	2.943	2.811	4.5

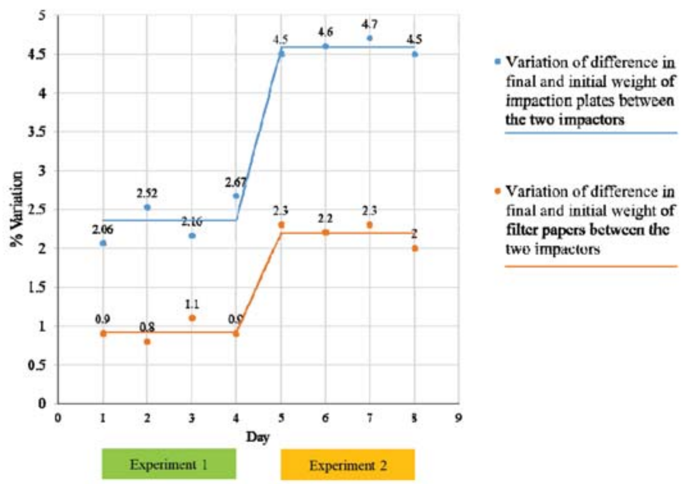

Figure 3. Variation of differences in the final and initial weight of impaction plates and filter papers between the two impactors.

The impaction spots were observed and measured with the Dino-Lite digital microscope (Figure 4). In experiment 2, the individual impaction spots (N = 4) on the impaction plate of the off-centric impactor were much smaller and look lighter than the singular impaction spot obtained in case of the conventional impactor. However, the total area of the four impaction spots (in case of off-centric impactor) is larger than the area of single impaction spot obtained while utilizing a conventional

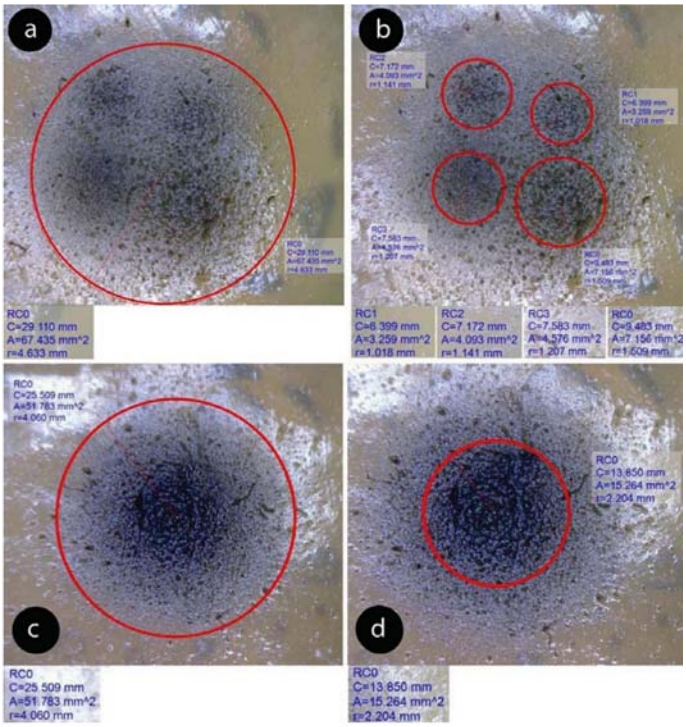

Figure 4. Area estimation of the impaction spots from experiment 2. Above figures showing: a. total area as predicted for off-centric impactor impaction plate, b. area near the central region as predicted for off-centric impactor impaction plate, c. total area as predicted for conventional impactor impaction plate, d. area near the central region as predicted for conventional impactor impaction plate.

impactor which clearly indicates towards better utilization of the impaction surface in case of the off-centric impactor. Lighter spots indicated less particle accumulation at a single impaction zone. Thus, the tendency of particle bounce-off would have reduced with the utilization of larger impaction areas in the newly designed off-centric impactor $PM_{2.5}$ sampler.

The weight difference of the captured particles on the filter substrate by the off-centric impactor showed a factor of 2 higher values as compared to that in experiment 1 (Table 5, Figure 3). This is attributable to the reduction of particle bounce-off and hence better capturing of target particles (here $PM_{2.5}$) on the filter substrate. The FESEM analysis was performed for both the filters. It showed both the impactors captured $PM_{2.5}$ on its filter substrate (Figure 5). The results from experiment 2, shown in figures 5, are similar to the observations reported above from experiment 1. And therefore, we would not reiterate here the discussion on it.

Table 5: Difference in final and initial weight of the filter substrate for both impactors in experiment 2.

Sample ID	Difference in final and initial weight of filter paper for off-centric impactor (mg)	Difference in final and initial weight of filter paper for conventional impactor (mg)	Variation (%)
Ex2 (Day 5)	1.939	1.894	2.3
Ex2 (Day 6)	1.746	1.706	2.2
Ex2 (Day 7)	1.823	1.780	2.3
Ex2 (Day 8)	1.942	1.903	2.0

4. Limiting the uncertainty

Although the present study conclusively indicates higher efficiency of off-centric impactor compared to the conventional impactor, few limitations need to be highlighted. Similar sets of experiments were conducted to minimize the handling error and gravimetric error. Multiple locations of the same filter paper were analyzed in FESEM for minimizing related uncertainty. The weighing machine was properly calibrated before

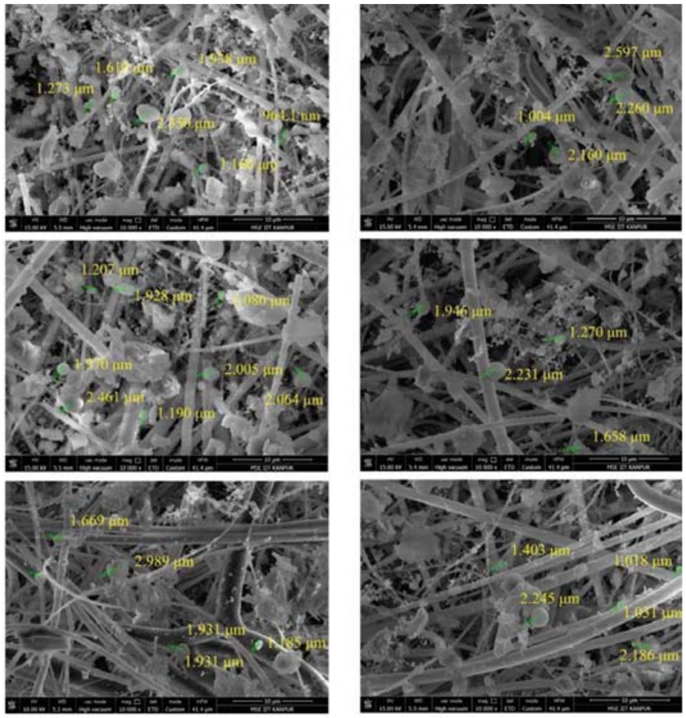

Figure 5. Field Emission-Scanning Electron Microscope (FE-SEM) analysis of aerosol laden filter retrieved in experiment 2 from off-centric impactor.

experiments. The uncertainty related to the low sample size has been reduced by using rigorous statistical analysis. A more sophisticated computational fluid dynamic modelling will be done for simulating the result from the experiment in the near future. Finally, estimating measurement uncertainty was beyond the scope of the study as establishing superior efficiency of the novel impactor compared to the conventional impactor was always the primary focus.

5. Conclusion

This study has presented a comparison of a novel off-centric impactor ($PM_{2.5}$, 15 LPM) with a conventional impactor. The filters collected from both impactors were subjected to gravimetric and FE-SEM analysis. The gravimetric analysis revealed that weight of the collected particles on the filter from the off-centric impactor is systematically higher as compared to conventional impactor which can be interpreted as the result of the reduction in particle bounce-off due to the off-centric impactor design. From the results of FE-SEM analysis, it is imperative to conclude that the off-centric impactor satisfies its $PM_{2.5}$ cut-off diameter at 15 LPM flow rate. In a nutshell, it can be concluded that with the use of the novel $PM_{2.5}$ off-centric impactor, more reliable particle data can be obtained with less particle bounce-off and without disturbing the designed particle cut-off.

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