



Linking Ambient and Duct Particle Size Distributions to Optimize Scrubber Performance in Industrial Ventilation Systems: A Practical Alternative to Isokinetic Sampling

Kian Dana¹, Somaye Hoseini², Mohsen Nikjo³, Pouria Dana⁴, Mahdi Jamshidi Rastani^{2,*}

¹ New York University, New York, USA

² Shahrood University of Medical Sciences, Shahrood, Iran

³ Shahrood Municipality, Shahrood, Iran

⁴ Environmental and Occupational Health Research Center, Shahrood University of Medical Sciences, Shahrood, Iran

*Corresponding Author: Shahrood University of Medical Sciences, Shahrood, Iran. Email: jamhosn@gmail.com

Received: 24 September, 2025; Revised: 3 December, 2025; Accepted: 6 December, 2025

Abstract

Background: The effectiveness of particulate air scrubbers in industrial settings is closely linked to an accurate understanding of particle size distribution (PSD). Isokinetic sampling is the standard approach for PSD measurement, though it presents operational challenges such as complex instrumentation and flow disturbances during sampling.

Objectives: This study aimed to evaluate the correlation between PSD in the workplace environment and the airflow inside the local ventilation duct of an iron manufacturing facility. It also assessed the efficiency of the existing scrubber system in controlling particle pollutants.

Methods: A cross-sectional descriptive study was conducted at an iron manufacturing unit, where PSD was measured three times at 17 pollutant-emitting sources connected to a single ventilation system. A four-stage cascade impactor was used to categorize particles into four size ranges: $< 1 \mu\text{m}$, $1 - 4 \mu\text{m}$, $4 - 15 \mu\text{m}$, and $> 15 \mu\text{m}$. Isokinetic sampling based on BS 3405 standards was performed inside the main duct leading to the scrubber. Data were analyzed using SPSS v16.

Results: The results showed that there was no statistically significant correlation between the PSD of airborne pollutants in the duct before and after the scrubber ($r = 0.476$, $P\text{-value} > 0.05$), nor between the PSD after the scrubber and in the workplace air when the system was ON ($r = 0.362$, $P\text{-value} > 0.05$). In contrast, strong and statistically significant correlations were observed between the PSD in the duct before the scrubber and the workplace air when the system was ON ($r = 0.958$, $P\text{-value} \leq 0.05$) and OFF ($r = 0.763$, $P\text{-value} \leq 0.05$), as well as between the PSD in the workplace air when the system was OFF and at the chimney outlet ($r = 0.876$, $P\text{-value} \leq 0.05$).

Conclusions: Ambient air PSD measurements can serve as a reliable alternative to internal duct measurements for evaluating and redesigning scrubber systems. It is recommended that this approach be tested across various pollutants to enhance its applicability and reliability.

Keywords: Particle Size Distribution (PSD), Work Ambient Air, Pollutant Source, Scrubber, Isokinetic Evaluation

1. Background

Airborne dust particles are an important component of indoor and outdoor air pollution and a key determinant of human and environmental health. In healthcare settings, dust and associated bioaerosols can act as vehicles for hospital-acquired infections,

especially when ventilation is inadequate, highlighting the importance of air-quality control in preventing pathogen transmission (1). Epidemiological evidence further links elevated particulate air pollution to increased incidence of serious cardiopulmonary outcomes such as pulmonary embolism (2), while particulate pollution in urban areas can also impair

plant physiology and reduce the resistance of sensitive species to environmental stressors (3). These findings underscore that effective control of dust particles – particularly in industrial workplaces where concentrations may be high – is essential for protecting both workers and the broader environment.

The aerodynamic equivalent dimension (AED) of particulate matter (PM) allows for the division of the particle size fractions into categories such as PM₁₀, PM_{2.5}, and Ultra-Fine Particulate Matter (UFPM) (4). While PM₁₀, PM_{2.5}, and UFPM penetrate the lower airways, particles bigger than 10 µm are unlikely to do so since they will mostly be filtered by the nose and upper airways (5-7). Larger particles (PM₁₀) will settle in the more proximal conducting airways, whereas smaller particles (PM) are assumed to penetrate and deposit into the deeper airways, such as the terminal bronchioles and alveoli (8-12). Over the last few decades, it has been evident that exposure to ambient air pollution, both short-term and long-term, is a huge risk factor for cardiovascular disease, which includes stroke (4,13-15).

According to estimates, the ninth-highest risk factor for the worldwide burden of disease is poor indoor air quality (IAQ) (16). In 2012, the World Health Organization reported that, compared with 3.7 million deaths from ambient outdoor air pollution, over 4.3 million premature deaths have been attributed to household air pollution (17). Moreover, it is estimated that total exposure to outside PM_{2.5} in China amounts to 66 - 87%, which is due to the indoor environment (18). The main IAQ metric is PM, the sum of all solid and liquid particles suspended in the air (19, 20).

Particle mass concentration (P_{mass}) and particle number concentration (P_{num}) are usually used to measure atmospheric PM. The particle size distribution (PSD) is also an important feature of PM, namely either mass concentration or the number measured over several different particle sizes (21). Having an exact comprehension of particulate emissions is crucial in order to execute suitable management that will result in a cleaner surrounding (22). The size of the particles determines how far they may penetrate the respiratory tract. In studies which aim at identifying the main sources of PM in indoor environments and to gain an understanding of significant removal processes and residence time for PM, a PSD metric is often applied (23-25). Despite the existence of standards for the P_{mass} metric, very few are specific to the indoor environment,

and this is a problem because the variability of concentration and PSD can vary significantly from the outdoor environment (26). Observations which are not possible in P_{mass} or P_{num} alone can be made using the PSD metric (27, 28). There are substantial difficulties in assessing IAQ related to ventilation and pollutant emission sources for implementing corrective measures (29).

In general, air particles sampling is performed for evaluating occupational exposure of people to pollutants in the workplace (29), evaluating the efficiency and effectiveness of control measures (30-33), practical and accurate identification of pollutant primary emission sources as well as the potential ones, and their contribution to pollutant production (28, 34).

On the other hand, studying and determining the design of the released particles site is related to the calculation process, the ventilation system, and the scrubber. When there is a need to check the scrubber collection efficiency or the effectiveness of particle control systems while the particles' physical characteristics change, like the size of PM, sampling at the chimney and duct are the first and second goals for PSD detection respectively. Also, measuring particles' size is mandatory in the laws of controlling the pollutants released into the environment (35-37). For this purpose, isokinetic sampling is used, which guarantees that the aerosol sample taken is representative of aerosols airflow (29).

Considering the requirements for the isokinetic sampling process and the wide range of gas and flow conditions in the duct, having reliable sampling inside the duct for collecting a reliable portion of particles requires a complex, challenging, and time-consuming process (35). Isokinetic sampling needs more complex equipment and tools, which leads to problems, including the existence of cyclonic flow in the duct and testing it before sampling (29, 38). Also, it is suggested there is a considerable loss and underestimation of particulate emissions in isokinetic suction filters (39-41). In addition, there are potential problems in obtaining a representative sample using the isokinetic process in its current form to use the extracted sample for analysis with new technologies (42). Moreover, regarding tiny particles (10 µm <) results show that sampling via isokinetic methods would be unnecessary (43). As for the sampling probe in the isokinetic process, the probe edge shape can induce a huge difference in efficiency of

particles mass concentration (44). Nevertheless, it is easier to determine the size distribution of particles in the air of the work environment and near polluting sources compared to determining the size distribution of particles inside the duct and before the scrubber (which requires the isokinetic sampling method).

2. Objectives

This study was carried out to determine the relationship between the PSD in the workplace and the airflow inside the ventilation ducts in an ironmaking unit to help gather more knowledge to design a more accurate scrubber.

3. Methods

3.1. Study Design

The data used in this study were originally collected in 2011 as part of a Master's thesis project and form one component of a comprehensive and systematic evaluation of the local exhaust ventilation system. The research design and hypotheses related to the relationships between PSDs in the workplace and within the ventilation duct were defined a priori at the time of data collection; however, the present manuscript has only recently been prepared. As the dataset is entirely non-human and based on physical and environmental measurements, the reliability, validity, and scientific relevance of the findings are not inherently compromised by the passage of time. Consequently, the results remain scientifically robust and pertinent to the evaluation and optimization of local exhaust ventilation and scrubber performance.

The present research was conducted as a descriptive-cross-sectional and experimental study on the local suction ventilation system and the iron oxide process of an ironmaking unit in a steel industry. The pollutant under the control of this system was iron oxide dust. Emission sources were mostly surfaces. This ventilation system has a vast ducting network with 17 hoods, installed on pollution sources on three floors and a platform (33).

In line with the objective of this study – to evaluate the relationship between the PSD of airborne contaminants in the workplace and within the ventilation duct in order to support optimization and modification of scrubber performance – measurements were conducted at four distinct locations/operational

conditions. PSD and particle concentrations in workplace air were measured under two ventilation scenarios, namely with the ventilation system operating (ON) and switched off (OFF), using the NIOSH 600 method. In addition, isokinetic sampling in accordance with BS 3405 was employed to determine PSD in the ventilation duct upstream of the scrubber, as well as downstream of the scrubber at the chimney outlet.

Based on the study objective, several statistical analyses were performed. Paired (dependent) comparisons were used to assess (i) the effect of the ventilation system on workplace PSD by comparing ON versus OFF conditions and (ii) the efficiency of the scrubber by comparing PSD upstream and downstream of the scrubber. Independent (unpaired) comparisons were applied to examine the relationships between workplace PSD (under both ON and OFF conditions) and PSD measured upstream and downstream of the scrubber. Furthermore, Pearson's correlation coefficient was calculated to investigate the presence, strength, and direction of linear relationships between workplace PSD (for both ventilation ON and OFF) and PSD at the duct locations (pre- and post-scrubber). These analyses were used to determine the influence of the ventilation system on changes in PSD patterns and to quantify the degree of linear association between the evaluated measurement points.

The pollutant emission and ventilation system ducting positions in the mentioned unit were on three floors and one platform. This evaluation was distributed on different floors and parts in order to maximize the collections; therefore, the mentioned unit and the ambient sampling locations were divided into four main parts (the ground floor, the screens floor, and the hood floor number one) and the hood platform 15, 16, 17.

3.2. Sampling Tools and Equipment

Tools and equipment used in both the environmental and inside of the duct sampling sections (isokinetic): A flow measurement and control equipment is connected to a 30 L/min sampling pump (SKC) via plastic pipes. For separating particles, a four-stage cascade impactor, a Cascade Centripetal model with a volume flow rate of 30 l/min, and the cut-off point defined in Table 1 were used. Flexible connecting tubes, standard isokinetic sampling openings with different diameters, a digital scale model Libror Ael - SM40 Shimadzu, Japan with a sensitivity of 0.00001 grams, a sampling filter GF/A-21-

Table 1. Details of Cascade Centripetal Orifice Dimensions and Openings

Type and Number of Filters	Size Distribution in Cascade Impactor Stages	Air Velocity at the Orifice	Nozzle Diameter	Area	Stage	Orifice Dimension
1 GF/A (21 mm)	> 15 µm	615	0.2	0.812	1	0.4
1 GF/A or 1 millipore AA (21 mm)	4 - 15 µm	2470	0.1	0.203	2	0.2
1 GF/A or 1 millipore AA (21 mm)	1 - 4 µm	9850	0.05	0.0506	3	0.1
1 GF/A (60 mm) in the model of UK	1 < µm	-	-	-	4	-

60mm SKC, South Korea, a filter AA-21mm Millipore SKC, South Korea, desiccator, and silica gel, pitot tube L Shape (KIMO), screwdriver of the volume flow rate adjustment pump, clamps, tweezers, bags and containers suitable for carrying samples.

A multi-function ventilation characteristic measuring device, KIMO AMI 300, Kimo, France.

3.3. Sampling Locations

3.3.1. Procedure

The sampling method and equipment used in workplace air sampling depend on the sampling objectives, the type of pollutant, and the available equipment. The most common method of sampling and collecting particulate pollutants is dynamic sampling. In this method, an air mover is used to pass a specific air volume at a certain pressure and temperature over a sampling interface (45). Some sampling devices, including impactors and cyclones, are used for particle classification.

There are two essential locations and positions for particulate pollutant sampling. A sampling of particles from still air (environment with an airflow speed less than 0.5 m/s) and sampling of gas flow (for higher speeds) that carries aerosol particles (29). A sampling of the static atmosphere includes three main places of public air in the work environment, the person breathing area and the source of pollutant production (45), and sampling inside the ventilation duct is an example of sampling in the gas flow (second mode). In order to achieve the goal of the research, sampling was done in two parts of the ambient air and inside the ventilation duct (isokinetic).

3.4. Workplace Ambient Air Sampling

To evaluate the system's effect on the control of particles with different sizes as well as their

concentration in the areas covered by the ventilation system, in two modes of the ventilation system (OFF and ON), NIOSH Method 600 (with the change that instead of a cyclone, we used a four-stage cascade impactor with a flow rate of 30l/min) was used. Sampling was done in places near the emission sources and at the height of 1.8 meters from the ground (30-32, 46, 47).

After ensuring the quality of the silica gel inside the desiccator, the filters in Table 1 were prepared according to the manufacturer's recipe for the cascade impactor and numbered behind them. In order to record the initial weight, the filters were placed in a desiccator for 24 hours before sampling. According to the numbering done on the back of the filters, the media sampling sequence (cascade impactor) was prepared.

After visual inspection, the media sampling components were packed and tested in a clean laboratory-based condition. A thorough leak test was performed to ensure there were no wear, tear, abrasion, or damaged parts. The volumetric flow rate passing through the sequence was calibrated by a dry gas meter. To transport the media sampling from the laboratory to the sampling site and vice versa, suitable bags and containers were prepared.

To achieve the minimum sampling volume requirement and measurable concentration, cascade impactors were installed at the height of 1.8 meters. In the pointed places (in the unit), the pump was turned on. The details of the sampling conditions, including temperature, humidity, initial sampling time, sampling location, date, and time of the sampling, were recorded. The flow rate of the pump was continuously monitored during sampling. In the end, after recording the secondary sampling time, the pump was turned off. After isolating the inlet and outlet of the cascade impactor, the sample was transported to the laboratory in a carrying bag. To reduce the analysis error and stabilize the weight before re-weighing, all samples were placed in a desiccator with temperature and

humidity conditions for 24 hours before sampling. Finally, concentration calculations in different sizes were done accurately and completely. Along with each main sample series, an individual sampling frame was prepared as a travel reference sample. The calculations related to determining the density of dust in different sizes were done using the following formula.

$$C = \frac{(W2 - W1) - (B2 - B1) \times 10^3}{V} \quad (1)$$

$$V = Q \times T \quad (2)$$

C: The concentration of pollutants in the air in $\frac{\text{mg}}{\text{m}^3}$;

W1: The initial weight of the filter in mg; W2: The secondary weight of the filter in mg; B1: The initial weight of the reference in mg; B2: The secondary weight of the reference in mg; V: The volume of sampled air in liters; Q: The sampling flow rate in $\frac{\text{lit}}{\text{min}}$; T: The sampling duration in min (12).

3.5. Isokinetic Sampling

3.5.1. Preparation of Isokinetic Sampling Conditions

Process conditions and process equipment stoppage time were checked. Necessary agreement and coordination with the process supervisor regarding the production rate of the factory and the process were made to maintain the sampling conditions' reliability at the time of sampling (35).

After ensuring the quality of the silica gel inside the desiccator, the filters in Table 1 were prepared according to the manufacturer's recipe for the cascade impactor and numbered behind them. In order to record the initial weight, the filters were placed in a desiccator for 24 hours before sampling. According to the numbering done on the back of the filters, the media sampling sequence (cascade impactor) was prepared.

After visual inspection, the sampling sequence components were packed and tested in a clean laboratory-based condition. A thorough leak test was performed to ensure no wear, tear, abrasion, or damaged parts. The volumetric flow rate passing through the sequence was calibrated by a dry gas meter. To transport the sampling media from the laboratory to the sampling site and vice versa, suitable bags and containers were prepared.

3.6. Isokinetic Sampling Sequence (In-duct)

Sampling from inside the canal is done in two ways: inside the duct and outside the duct. It was not possible to make large holes in the duct of the ventilation system. Therefore, isokinetic sampling in the form of out-of-duct sampling (observing no temperature changes and placing the sampling media at the closest point to the inlet of the sampler) was used before and after the scrubber (36). This process was repeated three times to increase the precision at each point.

The probe and sampling method used have advantages and disadvantages. The simplicity of placing the probe inside the duct is the main advantage of using it. On the contrary, its disadvantage is that, before the start of sampling, a traversing motion is performed to measure the speed. Subsequently, for isokinetic sampling, it is assumed that the flow conditions remain constant (36, 48, 49).

Since the speed is measured before the start of sampling, the assumption of constant flow conditions (including speed) is considered a disadvantage for isokinetic sampling calculations.

In order to determine the mass distribution of particle size inside the duct, the media sampling sequence is used. This sequence includes a standard sampler inlet (with sharp edges and different sizes) on the sampling probe. The probe is similar to a pitot tube, after which a cascade impactor (without any leakage or blockage) is placed as an intermediary at the smallest distance from the sampler opening (36). With the help of an indicator (such as a pitot tube), it was ensured that the inlet of the sampler was aligned (180-degree angle) with the airflow in the duct.

Cascade impactor: Filtration and impingement are the two main techniques for separating, removing, and collecting particles from the air. A cascade impactor works based on the phenomenon of particles hitting a solid surface. In this study, in order to analyze the PSD, a cascade impactor was used. A cascade impactor is designed to determine the mass density of particles and also determine the size of particles (36, 48-50). Therefore, in this study, the size distribution before and after the filter was investigated using the isokinetic method and the 3405BS method from outside the duct (35, 36).

1. To determine the cross-sectional area of the duct in the current situation, the diameter size was determined

by inserting a gradient pitot tube into the ducts.

2. Determining duct speed indirectly by measuring pressure (to solve potential problems, easier and faster measurement) can be a suitable method for determining the speed. Due to the changes in the airflow density of the duct and the non-uniformity of the flow, different results will be obtained from the measurements of the speed and volume flow rate of the volumetric air in a plane. Therefore, according to Wilson's grid method and recommendations of BS 3405, at the recommended points, the duct hole was drilled in equal spaces, at 10 points in each diameter, and for at least 10 seconds, the velocity pressure was measured using a pitot tube (with a cross-sectional area less than 1/20 of the duct's). The measurement results were recorded on the round duct survey movement registration sheet. Next, using the following relationship, the pressure at each point was converted to speed and calculated.

$$V = 174 \sqrt{P_v \frac{(t + 460)}{k \times d}} \quad (3)$$

Due to the high concentration of dust in the duct, after each use, the holes related to SP and TP on the pitot tube (pressure umbilical) were cleaned again by taking compressed air inside them. In other words, it was ensured that it was clean and healthy. In order to determine the volume flow rate (Q), the average speed (obtained from individual measurements) obtained by the cross-survey movement method was multiplied by the cross-section of the flow ($Q = V \times A$).

It should be mentioned that in order to prevent the effect of airflow speed on the static pressure measurement results (before and after the filter), the static pressure is measured at an angle perpendicular to the flow direction. Therefore, before the scrubber, static pressure measurements were made by connecting one end of the hose to the outer path of the pitot tube (side outlet of the pitot tube) and the other end of the hose to the KIMO and placing the pitot tube in the center of the duct. Also, a pressure gauge was installed on the duct wall after the cleaning to measure the static pressure after the scrubber and before the fan (30-32, 45, 51, 52).

Based on the recommendation of the 3405 BS method, sampling (and speed measurement), before the scrubber and the fan, at a distance of 4d (d = 90.6 cm) (downstream of a 45° elbow) and 2d (upstream of the last elbow), in two diameters and two locations was

done (4 samples). Sampling and size distribution of particles after the scrubber was done at a distance d4 (d = 125 cm) downstream of the fan in two diameters and two locations. The absence of cyclonic flow at the outlet of the system (chimney) was confirmed. The number of speed measurement points in the duct before the scrubber and in the chimney was determined as 10 points and 16 points, respectively (50), and the results of speed measurement were recorded. Based on the recommended volumetric flow rate in the impactor (30l/min), the following equation was used to calculate the cross-sectional area and diameter of the sampler inlet of the isokinetic sampling probe.

$$Q = 60 \times V \times \frac{\pi \times d^2}{4 \times 144} \quad (4)$$

V: Duct or flue velocity in feet per second; d: Inner diameter of sampling probe in inches

The size of the inlet opening and sampling probes were selected and determined with the help of a drill in different sizes. After selecting the probe and completing the sampling sequence, the pump was turned on and set to the desired volumetric flow rate (30l/min). Then, according to the 3405 BS method, out-of-duct isokinetic sampling was done at 4 points (in each cross-section) cumulatively by recording the details of the sampling conditions before and after the filter. Along with each sample, a travel blanks sample was included. After isolating the inlet and outlet of the cascade impactor, the sample was transported to the laboratory in a carrying bag. Before re-weighing (after sampling), in order to reduce the analysis error and to stabilize the weight, all samples were conditioned in temperature and humidity conditions before sampling (by placing them in a desiccator for 24 hours). The used equations were checked for compatibility with each other. Finally, concentration calculations in different sizes were done accurately and completely (35).

4. Results

After dividing the unit into four parts, air concentration measurement by a cascade impactor took place when the ventilation system was OFF and ON in different locations. The results of measuring the average dust in the whole unit with the help of a cascade impactor in the condition of the ventilation system ON and OFF and the overall effect of the system on the dust control are given in Tables 2 and 3. The results of the

Table 2. The Results of Measuring Particle Size Distribution in the Whole Unit with the Help of Cascade Impactor in the State of Ventilation System ON and OFF

Cascade Impactor Stages	Ventilation System OFF (mg/m ³)		The Ventilation System is ON (mg/m ³)	
	Mean ± SD	Maximum-Minimum	Mean ± SD	Maximum-Minimum
The stage 1 of the impactor (> 15 µm)	6.08 ± 34.45	8.76 - 44.45	18.86 ± 39.96	11.92 - 46.76
The stage 2 of the impactor (4 µm - 15 µm)	60.63 ± 67.66	15.1 - 154.33	63.75 ± 63.83	10.56 - 155.67
The stage 3 of the impactor (1 µm - 4 µm)	18.53 ± 21.92	2.75 - 64.1	14.53 ± 20.76	2.17 - 60.02
The stage 4 of the impactor (1 µm >)	10.67 ± 11.95	1.26 - 25.67	10.73 ± 11.42	0.94 - 25.22
Total impactor stages	109.50 ± 141.21	31.03 - 290.67	112.51 ± 131.99	21.07 - 285.36

Table 3. Statistical Analysis of the Overall Effect of the System on Dust Control

Cascade Impactor Stages	Maximum-Minimum (mg/m ³)	Mean ± SD (mg/m ³)	t-Test	P-Value
The stage 1 of the impactor (15 µm <)	0.5 - 6.93	4.91 ± 9.31	2.453	0.032
The stage 2 of the impactor (4 µm - 15 µm)	0.05 - 6.9	8.81 ± 4.43	2.224	0.048
The stage 3 of the impactor (1 µm - 4 µm)	0.95 - 3.07	1.01 ± 2.96	1.134	0.281
The stage 4 of the impactor (1 µm >)	0.59 - 1.81	0.56 ± 1.72	1.08	0.303
Total impactor stages	2.89 - 12.61	10.91 ± 18.92	2.995	0.012

overall efficiency of the system in the control of the pollutants in the work environment are given in [Table 1](#).

The statistical analysis of the ventilation system effect (Paired *t*-test) on the average removal of dust in the first and Stage 2s of the impactor and the overall dust showed a significant difference (P-value < 0.05), but nothing was observed in the 3rd and 4th stages ([Table 3](#)).

The results of the passing pollutant concentration inside the duct before the scrubber and inside the chimney (after the scrubber) are given in [Table 4](#). The highest concentration before and after the filter are particles of 15 µm < and 1 µm > with values of 2847 mg/m and 365 mg/m respectively. The highest removal efficiency is for particles with a size of 15 µm and a value of 93.2%, and the lowest efficiency is for particles with a size of < 1 µm and a value of 30.4%. It should be mentioned that the whole scrubber provides efficiency of about 85/93. The removal efficiency values of different pollutant sizes by the scrubber are given in [Figure 1](#).

The results show that the average concentration of dust in front of the venturi scrubber is 6900 mg/m³, of which 4.7% is particles with a size of < 1 micron (525 mg/m³), 10.6% are particles with a size of 1 - 4 micron (728 mg/m³), 40.5% are particles between 4 - 15 microns (774 mg/m³), and 41.5% are particles > 15 microns (2847 mg/m³) ([Table 4](#)).

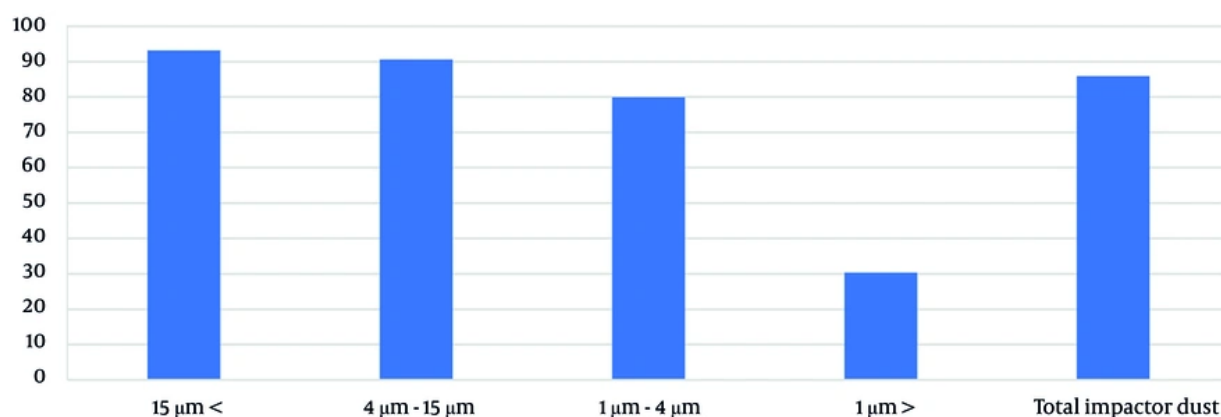
The results show that the average concentration of dust after the venturi scrubber is 965 mg/m, and 15.1% of the particles are 1-4 microns in size (146 mg/m), 37.8% are with a size below one micron (365 mg/m), 26.9% are between 4 - 15 microns (159 mg/m), and 20.2% are larger than 15 microns (195 mg/m) ([Table 4](#)). The results of the Independent *t*-test show a significant (P-value < 0.05) difference between the pollutant concentration in different sizes before and after the venturi scrubber as well as the scrubber impact on the dust removal in all stages of the impactor (18) ([Table 5](#)). The results of the scrubber efficiency are also given in [Figure 1](#).

The results of Pearson's statistical tests between PSD in the ventilation duct leading to the scrubber, the outlet of the scrubber, and the workshop environment in the two states of the ventilation system ON and OFF are given in [Table 6](#). The results show no significant (P-value > 0.05) relationship between the PSD before the scrubber and at the chimney outlet as well as those in the environment when the system is ON, compared to the chimney outlet. But there is a significant relationship between PSD before the scrubber and in the environment when the system is ON and OFF, as well as in the workplace air while the system is OFF and those at the chimney outlet (P-value < 0.05).

5. Discussion

Table 4. The Results of Measuring the size Distribution of Passing Particles Inside the Duct Before and After the Scrubber (Chimney)

Cascade Impactor Stages	Before the Scrubber		After the Scrubber	
	Maximum-Minimum (mg/m ³)	Mean $\pm$ SD (mg/m ³)	Maximum-Minimum (mg/m ³)	Mean $\pm$ SD (mg/m ³)
The stage 1 of the impactor (15 μ m <)	1928.6 - 3716.3	892.5 $\pm$ 2847.8	89.8 - 269.3	94.9 $\pm$ 194.8
The stage 2 of the impactor (4 μ m - 15 μ m)	1986.5 - 3501.6	764.7 $\pm$ 2774.5	125.5 - 368.7	125.6 $\pm$ 159.7
The stage 3 of the impactor (1 μ m - 4 μ m)	467.3 - 935.4	237.5 $\pm$ 727.9	54.9 - 226.5	87.4 $\pm$ 146.4
The stage 4 of the impactor (1 μ m >)	189.6 - 827.8	321.2 $\pm$ 524.8	205.4 - 511.6	153.4 $\pm$ 365.5
Total impactor stages	4678.8 - 8969.6	2141.7 $\pm$ 6857.5	659.4 - 1270	305.3 $\pm$ 964.7

**Figure 1.** The Overall efficiency of the system scrubber in dust removal

According to the results, the concentration of total and respirable dust (smaller than 4 microns), in addition to being different, are more than the standard limits in OFF and ON conditions, which shows the ineffectiveness of the ventilation system. According to the field investigation, the ineffectiveness of the ventilation system can be attributed to its size, improper maintenance, the long life of the system, and not being in compliance with the recommended standards (33). Results show no significant difference in the 3rd and 4th stages of the impactor, which can be related to the low weight of the particles distribution, which forms the smallest size of particles (P-value < 0.05). In addition, since the environment was semi-open, the PSDs less than 4 microns can be affected by the atmospheric pollutants or the tendency of them to stay suspended longer; which indicates, the statistically significant (P-value < 0.05) lack of effectiveness of the ventilation system in controlling smaller size particles. In the study of Tippayawong et al., it is emphasized that

a significant share of particles inside the building can be due to the penetration of particles in the open space (53), and in the study of Saral, it is also mentioned the resuspension of dust particles with a diameter of 3.3 micrometers (54). The study by Cao et al. also refers to the impact of indoor pollutants on outdoor pollutants (55).

In addition, the results of Tables 2 and 3 and Figure 2 show that the average concentration of general and respirable dust (smaller than 4 microns) is much more than what is recommended by OSHA (33). Also, the results of Figure 2 show that the mentioned system does not have the necessary efficiency and effectiveness in controlling the pollutants.

According to the results of Table 4, pollutants with a larger size occupy a more extensive distribution of pollutants inside the ventilation duct before the scrubber, while pollutants with a smaller size have the most considerable amounts after the scrubber. According to the results of Table 5 and Figure 1, the

Table 5. The Results of Measuring the Size Distribution of Passing Particles Inside the Duct Before and After the Scrubber (Chimney)

Cascade Impactor Stages	Maximum-Minimum (mg/m ³)	Mean $\pm$ SD (mg/m ³)	t-Test	P-value
The stage 1 of the impactor (15 μ m <)	2368.4 - 2916.8	431.6 $\pm$ 2640	21.21	0
The stage 2 of the impactor (4 μ m - 15 μ m)	2273.4 - 2738.7	2510 $\pm$ 366.1	23.71	0
The stage 3 of the impactor (1 μ m - 4 μ m)	507.1 - 655.4	116.7 $\pm$ 581	17.25	0
The stage 4 of the impactor (1 μ m >)	57.8 - 260.8	159.7 $\pm$ 159	3.46	0.005
Total impactor stages	5370.3 - 6408	816.6 $\pm$ 5890	24.94	0

Table 6. Statistical Analysis of the Overall Effect of the Scrubber on Dust Removal

Sampling Location	Inside the Duct Before the Scrubber	System Environment ON	System Environment OFF	Chimney
Inside the duct before the scrubber				
Pearson correlation	1	0.985 ^a	0.763 ^b	0.476
Sig. (2-tailed)		0	0.017	0.195
System environment ON				
Pearson correlation	0.985 ^a	1	0.666 ^b	0.362
Sig. (2-tailed)	0		0.05	0.338
System environment OFF				
Pearson correlation	0.763 ^b	0.666 ^b	1	0.867 ^a
Sig. (2-tailed)	0.017	0.05		0.002
Chimney				
Pearson correlation	0.476	0.362	0.867 ^a	1
Sig. (2-tailed)	0.195	0.338	0.002	

^a Correlation at a meaningful level 0.01.

^b Correlation at a meaningful level 0.5.

scrubber efficiency is confirmed in terms of the statistical test; while we know that from the technical point of view and the design characteristics of venturi scrubbers (pressure drop, liquid-to-gas ratio, throat velocity, and flow rate), the scrubber investigated in this study does not have enough efficiency even for large particle sizes (56). In this study, which was conducted in a steel industry to research the correlation between the PSD and their concentration in the workplace air (while the ventilation system was ON and OFF), as well as before and after the scrubber (56).

Regarding the relationship between PSD in the workplace air and those in the duct before and after the scrubber, the results show that there is a difference between those in the duct before the scrubber and those in the chimney (that is, before and after the scrubber). According to the performance of the purifier, different sizes of particles are removed (mostly larger particles) and it causes a change in the PSD downstream of the purifier and the chimney outlet. That is why there is no

correlation between the PSD at the chimney outlet and the air of the working environment. Since the pollutant source emitting inside the duct is in the workplace air before the scrubber, pollutants are sucked into the duct by the turned-ON ventilation system. According to Figure 1, the size distribution of the pollutants at the chimney exit is different from those in the workplace air and before the scrubber, thus the result was not far from expected.

A study done by Shin et al. illustrates the fact that a probe sampling device has the ability to execute near-flawless sampling of tiny particles while maintaining consistent sampling flow rates. It also minimizes inaccuracies in particle measurement caused by non-uniform sampling for varying flow velocities (57).

Another study from the current study team shows the effect of size distribution and removal efficiency (56). The relationship between the effect of the chimney exiting pollutant on the pollutant size distribution in the air of the workplace and the effect of the pollutant

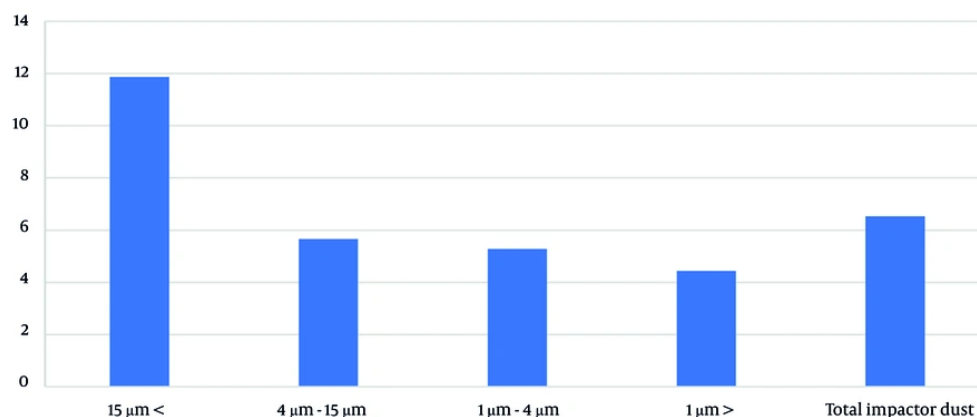


Figure 2. Overall estimation of the comparison of dust distribution in the whole unit

size distribution produced and presented in the workplace air (due to the process of the chimney outlet) can be considered a two-way relationship. The outdoor pollutants' effect on the indoor environment has been highlighted in various studies, for example, in the study of Hussein et al., they stated that the patterns of air pollution of fine particles in the indoor environment could be primarily estimated based on the aerosols characteristics in the outdoor environment and mechanical ventilation system (58). But there was no significant relationship between the PSD of indoor air pollutants when the ventilation system was ON and the PSD in the chimney (P-value < 0.05).

The reason for this is the lack of adjustment of the PSD discharged from the chimney by the outdoor environment, therefore, it cannot be explained by the definition of the penetration factor (which is a useful factor to describe the amount of indoor particles and a good indicator of balance fraction (I/O ratio) which penetrates into the indoor environment and remains suspended)(59).

In addition, the high amount of air particles in the working environment resulting from the process in different sizes and its lack of noticeable influence on the size of the chimney outlet pollutant can justify this misrelation.

On the other hand, ineffective and misrelation between PSD in the working environment when the system is ON and the chimney outlet can be due to the

difference in the scrubber efficiency at particles with different sizes.

There is a significant (P-value < 0.05) correlation in the 3rd and 4th stages of the impactor in the workplace air, between the PSD in the duct before the scrubber and the PSD in the workplace air, while the system is OFF and ON. Therefore, it can be concluded that the primary source of the air inside the ventilation duct (before the scrubber) is the air inside the hall. This result is reasonable and not far from expected when the ventilation system is ON, and the workplace air is drawn into the ventilation system (60). There is a significant (P-value < 0.05) relationship between PSD in the workplace air when the ventilation system is OFF and those at the chimney outlet when the system is ON. Which is the justification (and reason) for the lack of the ventilation system effectiveness on the average dust removal in different parts of the unit (Table 3), in the 3rd and 4th stages of the impactor in the workplace air and the two-way relationship between them. In other words, it shows the effect of the semi-open environment and the return of smaller-sized pollutants to the workplace air while more of them remain suspended in the workplace air.

In addition, the significant relationship between PSD in the workplace air when the system is OFF and ON (P-value $\leq$ 0.05), with consideration of the fact that when the system is OFF, the same pollutants accumulate in the air, which is reasonable. Therefore, in order to check the PSD in the duct for proposing the type of scrubber and

its parameters in the mentioned system (or the compliance and efficiency of the parameters based on which the scrubber is designed or is operating), it is possible to analyze and distribute the particles' size that they are blown by the ventilation system or accumulated in the workplace air (60).

Various studies have pointed out the use of PSD in the design of the scrubber. In the another study, citing particle measurement methods (61) and the importance of having information about the concentration and size distribution of particles for the selection and design of removal systems, particles are also explicitly mentioned (62). Zhang et al.'s study also emphasizes the importance and purpose of using PSD to make decisions and select control techniques (63).

In addition, advanced gas-phase abatement technologies, such as hybrid non-thermal plasma – catalyst systems developed for VOC decomposition, could be integrated with mechanical particle scrubbers to provide more comprehensive control of co-emitted pollutants (64).

5.1. Limitations

The study faced limitations such as the complexities of isokinetic sampling, which may not reflect the real particle distribution inside the duct. The ventilation system also showed inefficiency, which impacted the particle control results. Additionally, the study was limited to iron oxide particles, and other pollutants were not considered, which could provide a broader understanding of scrubber performance.

5.2. Conclusions

The results of this study statistically confirm the relationship between PSD in polluted air before and after the scrubber with PSD in the workplace air. Even though the scrubber efficiency was approved in terms of the statistical test, a notable lack of effectiveness and efficiency of the ventilation system and the scrubber in controlling particle pollutants was detected. Since the isokinetic sampling method has its own problems and complexities, which usually do not present the real particles distribution, using the size distribution of ambient air pollutants instead of those inside the ventilation ducts (and before the scrubber), in terms of essential information for the use of redesigning and bug fixing the working refiners, is recommended. In addition, it is suggested that this review be done for

different pollutants for more reliance on this alternative.

5.3. Recommendations

It is recommended to redesign the scrubber based on the size distribution of ambient air pollutants rather than relying solely on measurements inside ventilation ducts. Future studies should focus on a wider range of pollutants to increase the reliability of the findings. Maintenance and upgrading of the ventilation system are essential to improve particle control efficiency.

Acknowledgements

We acknowledge the support provided by Shahroud University of Medical Sciences, New York University, and the technical assistance of the field staff involved in this study.

Footnotes

AI Use Disclosure: The authors declare that no generative AI tools were used in the creation of this article.

Authors' Contribution: Conceptualization: K. D. and M. J. R.; Methodology: M. J. R. and S. H.; Software: M. J. R.; Data curation: S. H. and M. N.; Writing-original draft preparation: K. D. and M. J. R.; Visualization: K. D.; Investigation: K. D., S. H., and M. N.; Supervision: M. J. R.; Validation: M. J. R.; Writing-reviewing and editing: K. D. and M. J. R.

Conflict of Interests Statement: The authors declare no conflict of interests.

Data Availability: No new data were created or analyzed in this study. Data sharing does not apply to this article.

Funding/Support: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

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