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Performance and Environmental Impact Assessment of Industrial Ventilation Systems for Internal Contamination Sources

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Abstract

For *different industrial facilities, indoor air quality is a crucial factor in assessing the work environment as it relates to the health and comfort of the workers. Industrial ventilation is mandatory, as contamination emission rates are often much higher than in non-industrial facilities. Rather than industrial air quality and occupants' comfort, industrial buildings have other vital factors that must be considered, such as environmental impact and energy consumption. The movement of contaminants (e.g., dust, fumes, vapors, aerosols, etc.) depends on the source shape and temperature, which are classified as diffusion contaminants sources, buoyant sources, and dynamic sources. An industrial building is commonly equipped with a general ventilation system, a local ventilation system, or a combination of both. However, due to the variety of industries producing a wide range of contaminants, special attention is required to employ the appropriate system. Thus, this study aims to address common types of industrial ventilation systems and new innovative designs such as spray local ventilation,* vortex ventilation systems, and other types. *Ventilation evaluation includes standard indices to assess the system's performance, including capture efficiency and air change per hour, the most common indices for local and general ventilation.*

1. Introduction

For several building facilities, indoor air quality (IAQ) is crucial in assessing the environment regarding the health and comfort of building occupants. An inadequate ventilation system may contribute to the accumulation of viral particles in indoor spaces, increasing the risk of infection. According to the United States Environmental Protection Agency (EPA), Americans spend approximately 90 percent of their time indoors, where pollutants may vary between two and five times. According to the World Health Organization (WHO), For several building facilities, indoor air quality (IAQ) is crucial in assessing the environment regarding the health and comfort of building occupants. An inadequate ventilation system may contribute to the accumulation of viral particles in indoor spaces, increasing the risk of infection. According to the United States Environmental Protection Agency (EPA), Americans spend approximately 90 percent of their time indoors, where pollutants may vary between two and five times. According to the World Health Organization

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Nomenclatures

Abbreviations

ACGIH	American conference of governmental industrial hygienists
CFD	Computational fluid dynamics
EPA	United States Environmental Protection Agency
IAQ	Indoor air quality
IDLH	Immediately dangerous to life and health
IVDGB	Industrial Ventilation Design Guidebook
LOAEL	The lowest observed adverse effect level
NIOSH	National institute for occupational safety and health
OELs	Occupational exposure limits
OSHA	The occupational safety and health administration
PEL	Permissible exposure limit
PM10	Particulate matter of size less than (10 µm) diameter
PM2.5	Particulate matter of size less than (2.5 µm) diameter
REL	Recommended Exposure Limit
SETAC	The society of environmental toxicology and chemistry
STEL	Short-term exposure limit
TLV	Threshold Limit Values
TWA	Time-weighted average
VOCs	Volatile organic compounds
WHO	World health organization

symbols

ACH	Air exchange rate per hour (h^{-1})
C_0	Ambient environment air concentration (mg/m^3).
C_e	The pollutant concentration with the hood opened in the calculation zone (mg/m^3).
C_{e0}	It is a pollutant concentration with the hood closed in the calculation zone (mg/m^3).
C_{ext}	Pollutant concentration in the extract of the hood (duct) (mg/m^3).
C_{max}	Target level concentration at room (mg/m^3)
C_r	Room pollutant concentration (mg/m^3)
C_{source}	The cumulative emission concentration (mg/m^3)
C_s	The pollutant concentration at the pollution source (mg/m^3).
G'	The rate at which contaminant is captured by the exhaust system (mg/s).
G	Rate of contaminant generation (mg/s).
Q	General ventilation rate. (m^3/h)
Q_{gen}	The general exhaust volume flow rate (m^3/s).
Q_{min}	a minimum ventilation rate (m^3/h)
Q_{vs}	Ventilation flow rate into and out of the space (m^3/s).
T_0	Temperature of the mechanical exhaust (K).
T_i	Temperature of the natural ventilation inlet (K).
T_n	Temperature of the occupied zone (K).
V_{ol}	Room volume (m^3).
η	capture efficiency
ψ	Time-varying contaminates escape ratio.
τ	time (min)

(WHO), The combined ambient and household air pollution effects are associated with 6.7 million premature deaths annually [1].From a research point of view, ventilation can be classified based on the building type into three main sectors, as shown in Fig. 1: residential, commercial, and industrial [2]. In industrial facilities, the contaminant emission rates may vary from ten to a hundred times higher than in non-industrial facilities [2]. Therefore, ventilation systems must be considered for industrial buildings to ensure an adequate environment for the workers. This study aims to address common ventilation system strategies and state-of-the-art innovative ventilation designs. Then, industrial air quality and environmental assessment, including the common organization and associations for occupational exposure limits of the hazardous substances, are provided with case studies. Then, performance indicators are addressed, followed by future work opportunities and a conclusion.

2. Industrial ventilation strategies

In general, industrial ventilation systems can be classified into general and local ventilation systems. As shown in Fig. 2, an example of a combined general and local industrial ventilation system illustrates the different flow types and the system's main components. Regarding polluted air, the system can be divided into two sets of components: components that deal with minor pollution associated with general ventilation exhaust and components that deal with significant pollution associated with local ventilation exhaust. Air cleaning is frequently integrated into the exhaust air unit for the general ventilation exhaust. Nevertheless, a segregated cleaning unit is utilized for local ventilation exhaust.

In the equations (eq. 1) and (eq. 2), the contamination generation rate $\mathrm{G}(\mathrm{mg}/s)$, a minimum ventilation rate $\mathrm{Q}_{\mathrm{min}}$ $(\mathrm{m}^3/\mathrm{s})$ is meant to maintain the concentration at a target level $\mathrm{C}_{\mathrm{max}}(\mathrm{mg}/\mathrm{m}^3)$, which can be calculated to replace polluted air with clean air, leading to dilute and decreased contaminant concentrations. The air exchange rate per hour (ACH) can be calculated for room volume V_{ol} (m^3), [3].

$$Q_{min} = \frac{G}{C_{max}} \qquad \text{(eq. 1)}$$

$$ACH = \frac{Q}{V_{ol}} \qquad \text{(eq. 2)}$$

In summary, the general ventilation system is appropriate under the following conditions:

- A local ventilation system is not approachable or inappropriate.
- Effective transport of the contaminant to the exhaust point is achievable.

A local ventilation system is mandatory, as those conditions cannot be achieved. In principle, and often in practice, all local ventilation systems can be manufactured in different modes: fixed, flexible, or mobile [2]. As shown in Fig. 2, the room volume can be categorized as controlled, uncontrolled, or capture zones for industrial workspaces with ventilation.

- Controlled Zone: The area where thermal and air purity conditions are regulated to specific levels. There are two categories:
  - Main controlled zone: typically, a large area, often within the occupied zone.
  - Locally controlled zone: an area where air is locally controlled, with requirements for worker protection and comfort, process control, or production protection.
  - Uncontrolled Zone: An uncontrolled zone lacks specified or regulated thermal and air purity conditions.

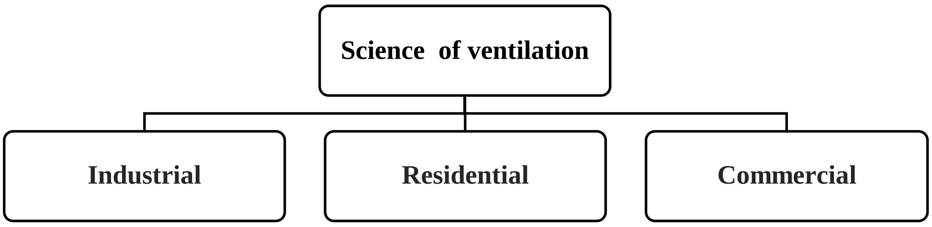

Fig. 1 Ventilation science.

- Capture zones are areas where source emissions are intended to be captured by a capturing system (local exhaust ventilation). From the perspective of pollutant concentration, the capture zone is considered uncontrolled.

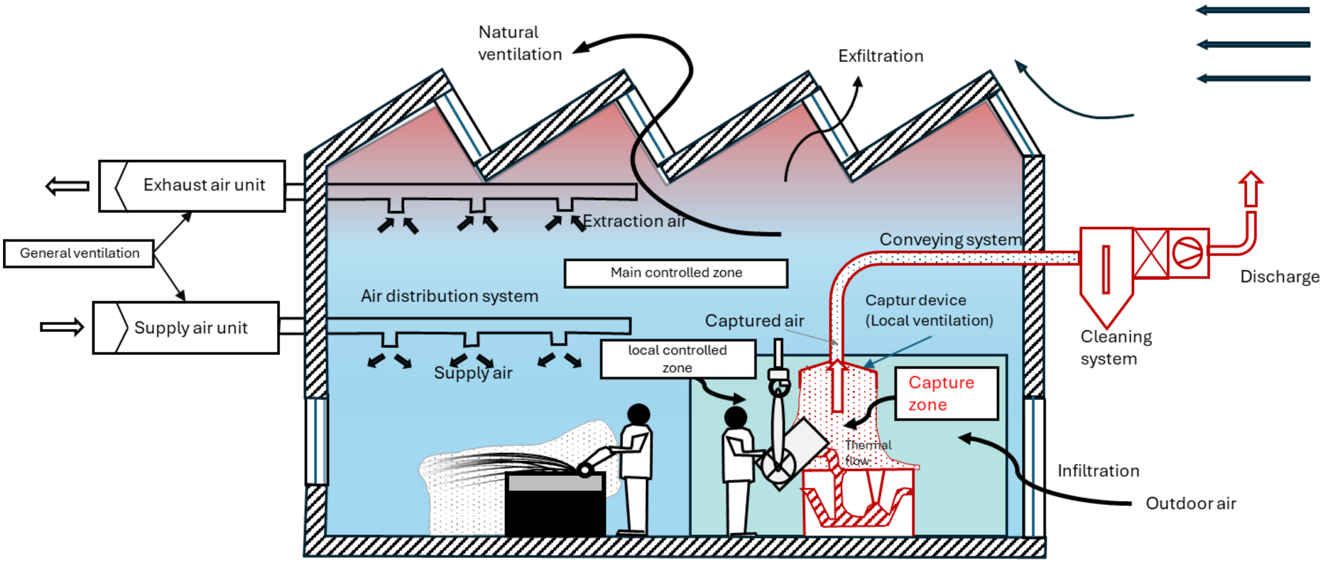

Fig. 2 combined general and local industrial ventilation system illustrating different flow types and the main components of the system.

Through studies, research, and the development of existing ventilation strategies, newer technologies and strategies are introduced to enhance system performance. The diagram shown in Fig. 3 illustrates common types of ventilation strategies. An innovative design of roof exhaust was introduced to overcome the presence of an overhead crane above the pollution source, as in that case, the capture efficiency of pollutants decayed as the roof hood got blocked by the overhead crane [4]. The proposed overhead crane fume-collecting hood is shown in Fig. 5. For numerical simulation to solve the continuity, momentum, and energy equations, CFD dynamics software ANSYS Fluent was used. The realizable k-ε turbulence model was utilized, where k is turbulent kinetic energy, and ε is the turbulent kinetic energy dispersion rate. The proposed design showed better pollution capture efficiency throughout the study than without the system. Implementing the new design may have some limitations in real life as different scenarios regarding variation in temperature, flow field characteristics, geometry of obstacles, and pollution sources may affect the hood's performance. Therefore, further research is necessary. Furthermore, a spray local exhaust ventilation system was employed to investigate its impact on the flow field and ventilation performance. The system utilizes the cooling and entrainment effects of spray droplets. The high-temperature airflow could be locally forced down and controlled for a typical application in a hot rolling mill, as shown in Fig. 4 [5]. The Realizable k-ε CFD model simulates airflow-droplet two-phase turbulence using ANSYS 2020 R1. The study employed orthogonal tests to analyze the independent effects of three key factors: initial spray droplet diameter, spray angle, and exhaust velocity. Furthermore, a dry fog dust suppression system was developed and experimentally investigated to control dust emissions, primarily from mining activities, and mitigate associated health and operational issues in the Donimalai iron ore mine located in Bellary district of Karnataka state in India. As illustrated in Fig. 6, ultrasonic and atomizing nozzles inject air and water at high pressure to suppress dust and maintain the contamination concentration of mg/m^3 and silica content under 5% [6].

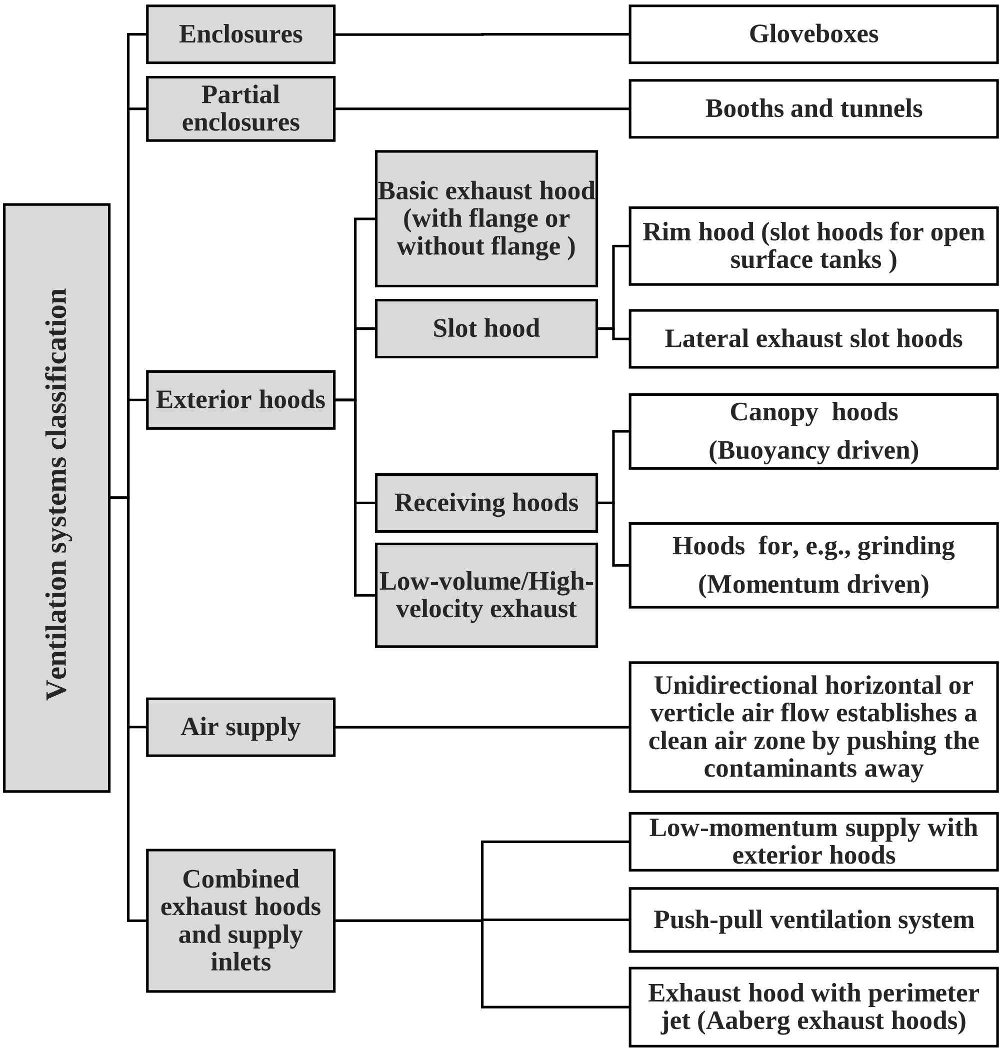

Fig. 3 local ventilation system classification

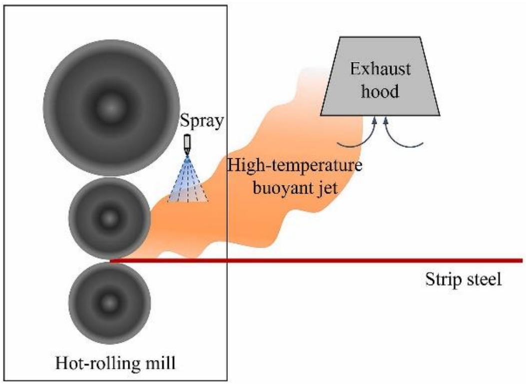

Fig. 4 Schematic diagram of a high-temperature buoyant jet of a hot-rolling mill controlled by spray local exhaust hood

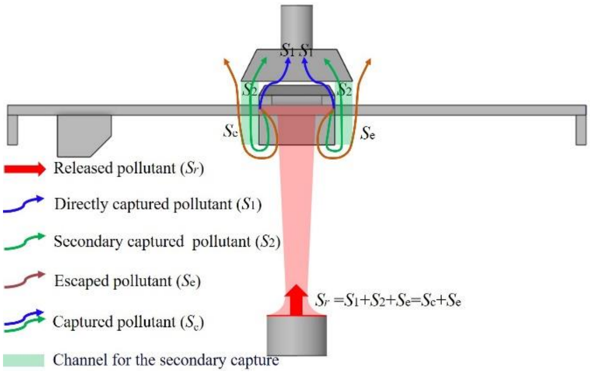

Fig. 5 Pollutant capture and escape mechanisms

Using the effect of spray droplets or fog to suppress dust and cooling may limit the humidity increase in the working area for the workers or the process. Therefore, each case analysis should be conducted to determine if that design is suitable for implementation. On the other hand, a novel Aarberg exhaust system reinforced by a swirling jet was proposed to evaluate the performance through a CFD simulation study compared to a basic Aarberg exhaust system and a conventional exhaust system by analyzing the airflow pattern, capture efficiency, and pollutant behavior [7]. The simulation model was implemented with the same design parameters as shown in Fig. 7. The study defined the momentum ratio term as the ratio of air jet momentum to hood suction air momentum. The center line suction velocity comparison at different momentum ratios showed that at a momentum ratio of 0.45 or higher, both the Aarberg hood and modified hood perform similarly. However, the difference becomes significant at a lower momentum ratio of 0.23. The modified hood performance is better than traditional Aaberg and conventional suction hoods. On the other hand, an experimental and numerical study has been implemented to investigate the effect of perimeter jet enhancement on capture velocity [8]. The hood structure design is shown in **Error! Reference source not found.** It was investigated by varying the jet velocity, jet angle, slot width, exhaust flow rate, and aspect ratio of the hood. There was no suitable formula for predicting the centerline velocity enhanced by a jet. Therefore, the experimental and CFD (using ANSYS Fluent) results could be utilized to propose formulas for predicting the centerline velocity of a rectangular air jet exhaust hood. An orthogonal experiment was conducted to analyze the effect of each factor on centerline velocity, including jet velocity, jet angle, and exhaust rate. The results showed that the maximum deviation of the centerline velocity calculated by the formulas as a percentage of the CFD simulated results was no more than 10%. The centerline velocity of the exhaust hood is mainly affected by the jet velocity, followed by the exhaust rate and jet angle. Throughout the study, innovative designs for modified supply jet hoods had the potential to enhance ventilation performance. However, it is more complex in a real-world industrial environment, and such a system may have limitations due to different obstacles and cross-drafts. Furthermore, the experiment investigated the combination of buoyancy-driven natural ventilation and a mechanical exhaust system in a prototype test room [9]. The study investigated ventilation performance with different mechanical exhaust velocities and different modes of hybrid ventilation. The temperature distributions and hybrid ventilation efficiencies were analyzed for different mechanical exhaust velocities.

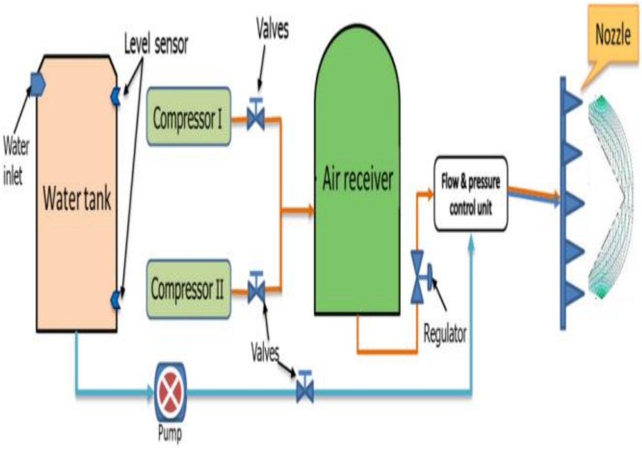

Fig. 6: Dry fog dust suppression system schematic diagram

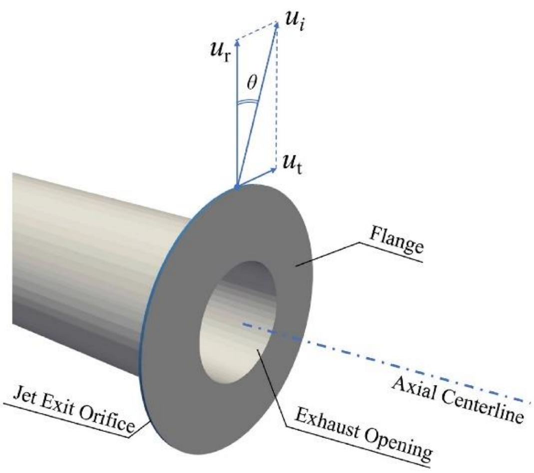

Fig. 7 Geometry of the hood .

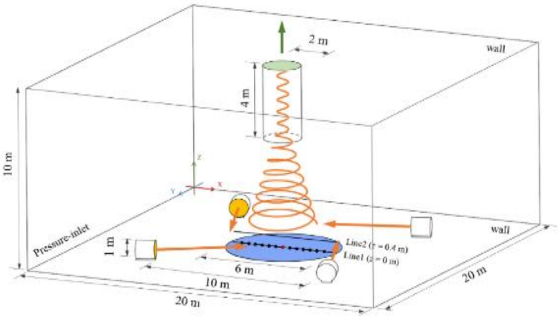

Fig. 8 the geometric model of the computational domain.

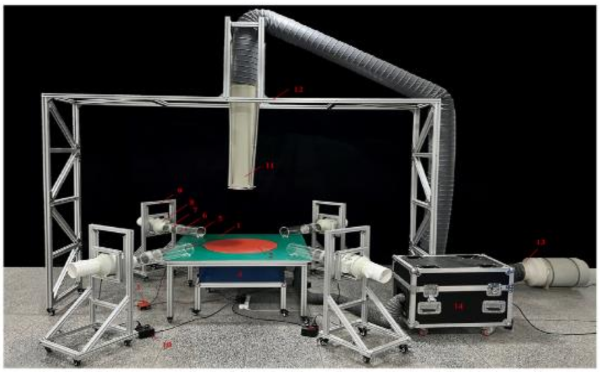

Fig. 9 The experimental setup

The scaled model dimensions were 1.5 m long, 0.9 m wide, and 1.5 m in height, as shown in [10]. Results showed that the hybrid ventilation efficiency first increased and then decreased with the mechanical exhaust velocity, as high mechanical ventilation velocity may lead to self-circulation. On the other hand, the effect of different pollution source buoyancy fluxes on the characteristic parameters of the vortex flow field and the pollutant capture performance of a vortex ventilation system were investigated by experimental and numerical simulation methods [10]. The numerical simulation model dimensions were 20 m × 20 m × 10 m (length × width × height), as shown in Fig. 8. Principal configuration of the experimental setup is illustrated in Fig. 9. In this study, the removal performance of the buoyancy-driven pollutants with vortex airflow is divided into four parts typically the high-efficiency zone ($\eta > 90\%$), low-efficiency zone ($\eta < 20\%$), transition zone ($20\% < \eta < 90\%$), and invalid zone. In the invalid zone, the capture efficiency is significantly reduced because of an unstable vortex generated by the air's excessive angular momentum, typically when the air supply velocity increases to 4 m/s. Results showed that two different transport patterns were observed: vortex-dominated and plume-dominated, depending on the influence of the buoyancy of the pollution source. Both patterns achieved high capture efficiency, but the vortex-dominated mode showed fewer particle capture times. Table 1 summarizes the ventilation systems' descriptions, advantages, and limitations. Nevertheless, many industries in the market produce pollutants that have not yet been covered in research. Therefore, for industrial ventilation systems, no such system validates or fulfills all requirements; there must be a compromise. Characteristics of ventilation systems are essential, and there are requirements for each industrial application, which makes this topic a field for improvement and enhancement.

3. Industrial air quality and environmental assessment

Industrial processes generating pollution can be classified according to the direct interaction of workers with pollution or not, as it has been generated in an isolated environment. The process must be analyzed to design a suitable ventilation system that guarantees a healthy environment for the workers and a clean exhaust for the outdoor environment.

Table 1 compares innovative designs and their advantages and limitations in different industrial contexts.

Reference	System description	Study type	Contribution and Advantages	limitations

[5]	A spray local exhaust ventilation system to control Polluted high-temperature buoyant jets in hot-rolling plants.	CFD numerical simulation study The Realizable k-ε model simulates airflow-droplet two-phase turbulence using ANSYS 2020 R1.	Compared to local exhaust ventilation, spray-local exhaust ventilation enhances the capture efficiency of the exhaust hood at the same exhaust velocity.	The effectiveness of the spray in controlling high-temperature buoyant jets decreases with an increase in the initial spray droplet diameter or a decrease in the spray angle. The complexity of the relation between the spray and exhaust hood makes it difficult to optimize the system performance.
[4]	overhead crane fume-collecting hood to enhance roof exhaust hood capturing efficiency degradation when overhead crane interferes with it	CFD numerical simulation study. A realizable k-ε turbulence model was utilized. ANSYS Fluent was used.	The overhead crane fume-collecting hood significantly improves pollutant capture efficiency by 49.9%-74.6% compared to scenarios without it. Guide the disturbed pollutants back to the roof exhaust hood when the over-crane interferes with the exhaust flow.	The proposed design applies to a specific application scenario.
[6]	dry fog dust suppression system for controlling air pollution in mineral processing (crushing and screening plant.)	Before and after industrial case study.	Compared to the water sprinkling dust suppression system, the system does not change the raw material's mass as water added to dust is less than 0.01% of the raw material. The system significantly reduces dust and free silica concentration in the work zone. It is an automatic working system.	The system's effectiveness may vary based on the specific characteristics of the dust. The system needs constant monitoring of water impurities, which may hamper the nozzle's working by clogging.
[7]	A novel Aarberg exhaust system reinforced by a swirling jet	CFD numerical simulation study. k-ω turbulence model and SIMPLE algorithm within OpenFOAM	The detached jet enhances suction performance, while the attached jet can confine pollutant dispersion, improving capture efficiency.	The system may require careful optimization to ensure effective pollutant capture in different installation settings and scenarios, as it is uncertain whether pollutants will follow the suction flow or be entrained and blown away by the jet, impacting the overall capture efficiency.
[8]	study of the effect of perimeter jet enhancement on the capture velocity of a rectangular exhaust hood	Experimental and CFD-based numerical simulation by ANSYS Fluent software study	It helps maintain a higher centerline velocity and improve ventilation efficiency.	Increasing centerline velocity requires more energy consumption,
[9]	Study the hybrid buoyancy-driven natural ventilation with a mechanical exhaust system	The experimental one-tenth scaled model has dimensions of 1.5 m long, 0.9 m wide, and 1.5 m in height.	As the mechanical exhaust velocity increased, ventilation efficiency increased and decreased. Combining buoyancy-driven natural ventilation and mechanical exhaust systems, hybrid ventilation can effectively minimize ventilation energy consumption.	In the real world, variable loads and boundary conditions require considerations to prevent performance issues such as short-circuiting natural ventilation outlets or interference with thermal plumes caused by high mechanical exhaust velocities.

[10]	vortex ventilation system to handle high-temperature buyout source	experimental and numerical simulation methods	It can capture high-temperature buoyancy-driven pollutants from industrial processes like welding and casting, enhancing indoor air quality.	Excessive angular momentum of the air supply can reduce the capture efficiency of the vortex ventilation system, leading to suboptimal ventilation performance.

3.1. Occupational exposure limits

Occupational exposure limits (OEL) are expressed as the concentration of hazardous substances, such as ppm or mg/m^3. OELs are established in many industrial countries regulations such as Occupational Safety and Health Administration (OSHA) Standards [11]. In different associations for health, safety, and the environment, such as the National Institute for Occupational Safety and Health (NIOSH) and The American Conference of Governmental Industrial Hygienists (ACGIH), guidelines for exposure time and magnitude thresholds are addressed and updated based on types of pollution. It's important to highlight that not all workers are adequately protected by OEL, and some may experience discomfort or adverse health effects within those limits [12]. Table 2 describes the OELs set by OSHA, NIOSH, and ACGIH. Table 3 gives brief examples of hazardous substances in OELs.

Table 2: Different types of OELs set by various organizations to protect worker health from airborne hazards.

NIOSH	ACGIH	OSHA
NIOSH TWA (Time-Weighted Average): This is the average concentration a worker can be exposed to over a 10-hour workday during a 40-hour workweek. **NIOSH STEL (Short-Term Exposure Limit):** This is the maximum concentration a worker can be exposed to for a short period (usually 15 minutes) and should not be exceeded at any time during the workday.[13]	**ACGIH Threshold Limit Values (TLVs):** These are recommendations set by the American Conference of Governmental Industrial Hygienists (ACGIH). Similar to RELs, they have TWA and STEL values. Additionally, ACGIH suggests that transient increases may exceed three times the TWA value for no more than 15 minutes or four occasions spaced 1 hour apart during a workday and cannot exceed five times the TWA value. [15].	**OSHA Permissible Exposure Limits (PELs):** These are the legal limits set by the Occupational Safety and Health Administration (OSHA) in the US. The TWA concentration for OSHA PELs must not be exceeded during an 8-hour shift of a 40-hour workweek [11], [13] [13].

Table 3: Examples of some hazardous substances' OELs by OSHA, NIOSH, and ACGIH

pollutant	OSHA	NIOSH	IDLH (NIOSH)	ACGIH
Carbon monoxide (Co)	TWA: 50 ppm	REL TWA: 35 ppm [200 ppm should not be exceeded at any time.]	1200 ppm	TWA: 25ppm
Carbon dioxide (CO_2)	TWA: 5000 ppm	REL TWA: 5000 ppm STEL:30 000 ppm	40 000 ppm	TWA: 5000 ppm STEL: 30 000 ppm
Nitrogen dioxide (NO_2)	5 ppm [ceiling value should not be exceeded at any time.]	STEL: 1 ppm	20 ppm	TWA: 3 ppm STEL: 5 ppm
Sulfur dioxide (SO_2)	TWA: 5 ppm	REL TWA:2 ppm STEL: 5 ppm	100 ppm	STEL: 0.25 ppm

Hydrogen sulfide (H_2S)	20 ppm [ceiling value should not be exceeded at any time.] 50 ppm [10-minute maximum peak]	10 ppm [10-minute]	100 ppm	TWA: 10 ppm STEL: 15 ppm

3.1. Exposure health effects.

The occurrence and severity of polluted contaminants' effects depend on the exposure frequency, duration, and magnitude of exposure. Recent significant epidemic events were examined, including SARS, H1N1 influenza, MERS-CoV, and COVID-19, and how effective ventilation strategies and crucial design features impact airborne transmission within indoor environments [14]. The study investigated the contribution of mechanical, natural, personal, mixed-mode, and other miscellaneous ventilation types. The study suggested designing ventilation systems by optimizing parameters like air change per hour, ventilation rate, airflow patterns, number and location of air inlets and exhausts, and airborne particle concentration to predict infection risk for a specific space.

Natural ventilation at an existing smelting foundry shop was investigated [15]. The study examined the particulate matter concentration, temperature distribution, and flow pattern during solid metal smelting with different furnace parameters, such as the impact of the cross-flow, opening degree of the furnace, and initial temperature. The study included two main process modes: when the furnace opens outwards to charge the materials and opens inwards after smelting. When the furnace opened outward (fresh materials added), particle concentrations of various sizes (PM1, PM2.5, PM10) were relatively low (0.08-0.85 mg/m3). In contrast, inward opening (molten metal ready) increased particle concentrations (0.17-1.29 mg/m3). The inward opening showed an increasing particle concentration with height, with breathing zone levels twice as high as the outward opening. This is likely due to the differing airflow patterns of the hot air released during each operation. In a blast furnace-tapping plant, temperature, velocity, and particle characteristics were analyzed through on-site measurements and the CFD model [16]. The research targeted a blast furnace tapping house of a steel plant in Hubei. The study focused on the particulate matter diameter of 2.5 microns (PM2.5). The dust-bearing airflow in the iron casting yard comprises high-temperature gas and soot particles, which are gas-solid two-phase flow. Temperature distribution on the 1.5 m height plane was observed below 31°C, which is suitable for workers to operate. The surrounding area above the main operational ditch was as high as 40°C. The PM2.5 concentration of the entire respiratory area is below 80µg/m3, considered mild pollution. As fresh air enters from low windows and gets partially extracted by a dust hood, the remaining air should exit through the skylight. However, dust particles may accumulate higher if the vent above isn't positioned correctly. This highlights the importance of proper vent placement for effective dust removal. Air quality was investigated in a screen-printing workshop in Novi Sad, Serbia. The study highlights the potential for hazardous air quality in screen printing workshops due to exposure to VOCs, formaldehyde, and ozone [17]. The study emphasizes the importance of proper ventilation, control measurements for pollution emissions, and air quality monitoring to ensure workers' health and safety in such environments. Pollution concentrations were measured every 40 minutes for 4 hours in five screen-printing facilities. The study found that the concentrations of total VOCs, formaldehyde, and ozone were interconnected, with their levels influencing each other. The levels of certain VOCs, particularly acetone, isopropanol, and methyl ethyl ketone, were found to increase significantly during printing activities, exceeding the recommended OELs set by OSHA and NIOSH. Furthermore, Air pollution was investigated in mineral processing in the Donimalai iron ore mine in India's Bellary district of Karnataka state[6]. Tests were carried out to measure the concentration of dust in both the working area and the adjacent buffer zone within the crushing and screening plant. In the working area, the PM10 concentrations were measured, ranging from 1202 to

1540 $\mu g/m^3$ with an average of 1394 $\mu g/m^3$. In addition, the PM2.5 concentration varied between 176 and 310 $\mu g/m^3$, averaging at 232$\mu g/m^3$. In the buffer zone of the crushing and screening plant, PM10 concentrations ranged from 185 to 250 $\mu g/m^3$ with an average of 213 $\mu g/m^3$ PM10 concentration in the buffer zone. Similarly, the PM2.5 concentration within this zone ranged from 148 to 200 $\mu g/m^3$, with an average value of 184 $\mu g/m^3$.which exceeds the permissible limit by the national air quality standards for 100 $\mu g/m^3$ PM10 and 60 $\mu g/m^3$ PM2.5.

4. Performance indicators

For industrial ventilation system design, it should be noticed that rather than IAQ and occupants' comfort, industrial buildings have other vital factors that must be considered, such as

- Environmental restrictions, regulations, and standards for pollutant emissions by local government or recommendations by international organizations.
- Process requirements.
- Energy consumption and running costs.

Therefore, ventilation systems can be addressed from different points of view, such as energy, environmental, and safety assessments. Industrial exhaust systems consume a considerable amount of energy during their operation. These systems' operation involves using electricity to drive the fan motor, which is responsible for extracting and supplying air to and from the building. The power required for this operation depends on the volume of airflow and the system's static pressure. Additionally, the exhaust air often needs cleaning before it can be released outside, introducing further resistance to airflow and increasing power demands. To maintain a balanced environment, supply air must compensate for the expelled exhaust air, which requires energy input. These systems typically operate for extended periods; therefore, their energy consumption can become significant. Integrating automation within ventilation, including indoor air quality monitoring systems, can significantly contribute to the system's energy efficiency.

In contrast, the potential of smart industrial ventilation was explored within the context of Industry 4.0 [18]. The study proposed new concepts for integrating innovative ventilation and smart fan features into industrial air handling systems. They discussed the transition from standard to smart fans, highlighting the potential of comprehensive monitoring and control of gas parameters, aerodynamic performance, noise, efficiency, and resistance to harsh operating conditions.

Nevertheless, performance assessment indexes were investigated to evaluate industrial ventilation exhaust hoods employing capture velocity, flow ratio, and capture efficiency [19].

Time-varying contaminates escape ratio (ψ) and exhaust hood temporal capture efficiency (η) can be utilized to evaluate the performance of a lateral exhaust hood for control of a pulsating buoyant jet adjacent to a steady high-temperature source generating a steady plume. The escape ratio was determined by the ratio of the integral concentration in the environment to the cumulative emission concentration [20]. Capture efficiency is defined for an exhaust hood as the ratio of the directly captured contaminant to the amount of generated contaminant [2]. The room mass balance in (eq. 3) for the hood and source area is determined, assuming the air is well mixed based on the conditions and expressions provided in Fig. 10, and the capture efficiency is evaluated. Capture efficiency can be defined as the ratio of the directly captured contaminant at the hood $Q_{ext}(C_{ext} - C_0)$ to the amount of generated contaminant at source G. Table 4 summarizes the performance indicators for the industrial ventilation systems.

$$\mathbf{G = Q_{ext}(C_{ext} - C_0) + (Q_{vs} + Q_{ext})C_0} \quad \text{(eq. 3)}$$

Ventilation efficiency is defined as the ventilation system's capacity to eliminate heat, as shown in (eq. 12). In industrial structures, heat sources often coincide with sources of pollution, and pollutants generally track heat flow effectively. Therefore, the patterns governing the efficiency of ventilation in extracting excess heat and pollutants remain consistent [9]. Burgess stated that capture efficiency is the best concept to measure hood performance [3].

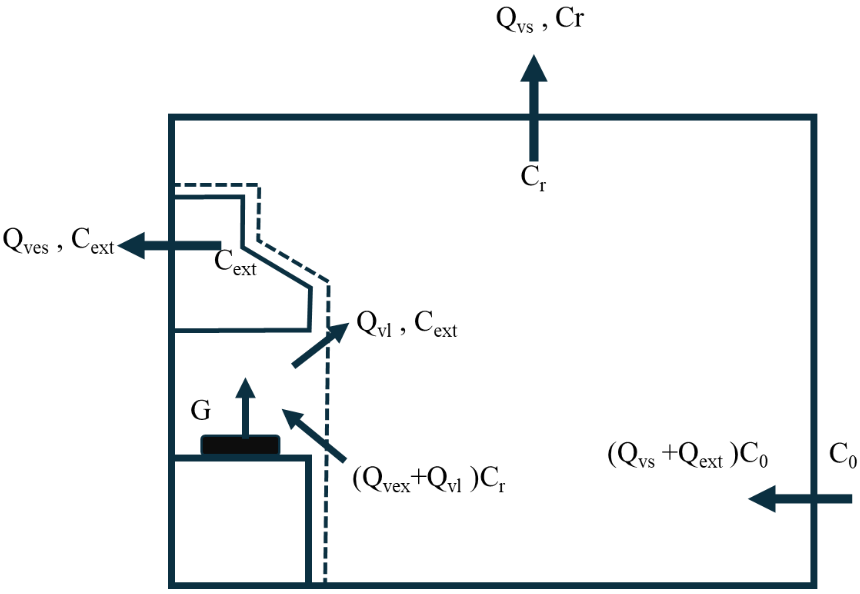

Fig. 10 Room mass balance boundaries for a contaminant source, local exhaust hood

Table 4 Common performance indicators for industrial ventilation systems

Reference	**Performance indicator**	**Equation**	**Remarks**
[3]	General ventilation efficiency	$\eta = \frac{G'}{G}$ (eq. 4)	The main definition of capture efficiency is the ratio of the rate of captured contaminants to the rate of produced contaminations.
[20]	contaminate escape ratio	$\psi = \frac{\int_{t=0}^{\tau} C_r\,dt}{\int_{t=0}^{\tau} C_{source}\,dt}$ (eq. 6)	τ (min): time period, (0≤ τ (min) ≤70) $C_0\ (ppm)$ is the ambient environment air concentration. $C_{source}\ (ppm)$ is the source of cumulative emission concentration.
[18]	Capture efficiency	$\eta = 1 - \frac{C_e}{C_{eo}}$ (eq. 7)	Hood capture efficiency is defined based on the ratio of the pollution concentration when the hood is opened to the pollution concentration when the hood is closed.
[20]	General ventilation combined with local ventilation. Capture efficiency	$\eta = \frac{C_{ext}\cdot Q_e}{C_{ext}\cdot Q_e + C_{gen}\cdot Q_{gen}}$ (eq. 8)	General ventilation is combined with local ventilation. Pollution capture efficiency is determined based on the general and local exhaust ducts.

[19]	Capture efficiency.	$\eta = \frac{C_{ext} - C_0}{C_s}$ (eq. 9)	If a contaminant, such as carbon dioxide, is present in the atmosphere. the concentration of the pollutant in the ambient is considered.
[2]	Capture efficiency	$\eta = Q_{ext} \cdot \frac{C_{ext} - C_r}{G}$ (eq. 10) Or, from (eq.3) $\eta = 1 - \frac{Q_{vs} + Q_{ext}}{G} \cdot C_r$ (eq.11)	As shown in Fig. 10 Capture efficiency can be defined as the ratio of the directly captured contaminant at hood $Q_{ext}(C_{ext} - C_0)$ to the amount of generated contaminant at source G.
[9]	Capture efficiency for thermal pollution.	$\eta = \frac{T_0 - T_i}{T_n - T_i}$ (eq. 12)	Ventilation efficiency is defined as the ventilation system's capacity to eliminate heat.
[19]	Capture velocity	-	The capture velocity of a hood is the air velocity created by the hood at the location where the contaminant is produced. Exhaust hood performance can be evaluated by comparing the pollution's capture and escape velocity at a given distance. Escape velocity at each point in the contaminant generation zone can be estimated by experiment or CFD. Capture velocity should overcome air currents and transport the contaminant to the hood. It is used to assess the control velocity method for hood design, which gives the distribution law of axial velocity for several hoods.
[19]	Flow ratio	-	Suppose the pollution emitted by the source is known or can be estimated. The flow ratio is the ratio of the exhaust rate of the hood to the pollutant emission flow rate.

5. Research gaps and future work

- Further research on the impact of automation and real-time monitoring of indoor air quality and performance indicators will utilize the data collected to identify peak pollution time and duration within the process to enhance energy consumption and provide better capture efficiency.
- Study the effect of particulate matter on size on the performance of the vortex ventilation system and the integration between the vortex momentum and particle settling velocity.
- A research study is needed to properly design multi-source local ventilation systems and determine how to control the stratification effect due to changing load (transient load).
- Study the performance parameters of multiple sources of contaminants handled by a single-hood versus multiple-hood approach. Furthermore, the influence of distance between multiple sources of contaminants on hood geometry and natural ventilation openings, including experimental and simulation-aided studies of the impact of side draft and different obstacles on contaminants' movement and ventilation efficiency.

- Dust suppression technologies significantly contribute to capturing efficiency and limiting pollution diffusion in the environment, which may contribute to lowering fan power consumption and has the potential for further study and research.

6. Conclusion

Industrial ventilation systems are necessary in industrial buildings to control contaminant emissions and provide a suitable indoor environment for workers and processes while complying with environmental regulations and the limits of harmful emissions by providing a sound cleaning system to ensure a clean exhaust. A general ventilation system is appropriate when occupants or workers are not exposed to excessive concentrations of contaminants. On the other hand, a local ventilation system is necessary when a general system is impractical or unsuitable for controlling environmental pollution. Using dry fog dust suppression systems in mineral industries to control dust emissions reduces dust and free silica concentrations in the work area. Fog suppression ventilation design performs well in mineral processing (crushing and screening plant.). Exposure assessment is crucial for evaluating the nature and severity of occupational hazards in the workplace, involving hazard identification, hazard characterization, exposure assessment, and risk characterization. Real-time monitoring of indoor air quality and performance indicators will utilize the data collected to identify peak pollution time and duration to enhance energy consumption and provide better capture efficiency. Regarding ventilation systems, professionals and specialized companies in this sector can consider the latest innovative industrial ventilation designs.

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