

## Research Article

# Preventing False Safety by Introducing the Hygienic Air Delivery Rate (HADR) for Mobile Air Purifiers

Fahmi Yigit <sup>1</sup>, Ayush K. Dixit <sup>1</sup> and Detlef Lohse <sup>1,2,3</sup>

<sup>1</sup>Physics of Fluids Group, Max Planck Center for Complex Fluid Dynamics, Department of Science and Technology, and J. M. Burgers Centre for Fluid Dynamics, University of Twente, Enschede, the Netherlands

<sup>2</sup>Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany

<sup>3</sup>Laboratory for Fluid Physics, Pattern Formation and Biocomplexity (LFPB), Göttingen, Germany

Correspondence should be addressed to Fahmi Yigit; [f.yigit@utwente.nl](mailto:f.yigit@utwente.nl)

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Indoor environments can become contaminated with pathogen-laden respiratory droplets exhaled by people, posing a risk of infection to others. To address this issue, indoor spaces are typically cleaned by ventilating—bringing in fresh outside air and expelling contaminated air. Mobile air purifiers can also help mitigate this risk and are widely used, particularly during emergent situations such as pandemics. However, a thorough assessment of how to measure the effective cleaning performance of air purifiers is still needed. Currently, the clean air delivery rate (CADR) is used as a standard metric to evaluate air purifiers. In this protocol, however, we identify steps that may erroneously influence the measured cleaning rate, potentially leading to falsely safe estimates. To address this, we propose a modified protocol to estimate the *hygienic air delivery rate* (HADR), which more accurately reflects the effective cleaning performance of air purifiers. We also suggest several considerations to enhance the HADR effectiveness of these devices. Additionally, we present case studies of real devices demonstrating that the HADR can be significantly lower than the volume flow rate of the air purifiers. We emphasize that the HADR—rather than the volume flow rate—should be used by both manufacturers and consumers to evaluate and compare devices, in order to prevent a false sense of safety.

## 1. Introduction

People spend approximately 90% of their time indoors, as confirmed by the WHO [1]. Consequently, indoor air quality plays a crucial role in human health and well-being [2–5]. This is especially important during a pandemic, when adequate ventilation of all indoor spaces becomes a critical health concern [6–8]. Proper ventilation, achieved through continuous air exchange, can be provided by permanently installed, typically centrally controlled, heating, ventilation, and air-conditioning (HVAC) systems [9, 10]. In this process, stale air—often contaminated with microbes [11] or elevated CO<sub>2</sub> levels—is replaced with fresh, unpolluted outdoor air, and contamination can be reduced significantly, as seen in healthcare facilities [12].

In addition to ventilation, air filtration techniques can be employed to reduce indoor contamination [13, 14]. These

systems do not exchange air with the outdoors but instead refurbish indoor air by removing, inactivating, or reducing bioaerosols and volatile organic compounds (VOCs) to acceptable levels [15]. However, removing CO<sub>2</sub> from indoor spaces remains more challenging [16]. These secondary air systems, often referred to as mobile air purifiers, are noncentral units placed within a room. Some models also offer the option to introduce fresh outdoor air. Notably, the use of air purifiers has been shown to reduce contamination levels by up to 90% when rooms are unoccupied and by an average of 50% during normal occupancy [17]. While air purifiers are effective in reducing airborne contaminants, they should not be regarded as substitutes for ventilation systems but rather as complementary or emergency solutions [18–25].

During the SARS-CoV-2 pandemic, sales of air purifiers surged [26], due to their ease of use and effective air cleaning

capabilities [13]. The pandemic underscored the ongoing challenge posed by pathogen-laden respiratory aerosols—a concern that remains relevant for the future. Given the ease with which bioaerosols can spread, they require sustained and careful attention [6, 7, 27, 28] and real bioaerosol tracking methods [29].

Although window ventilation is commonly used in indoor environments, it is only effective when there are significant thermal differences (due to weather) or pressure differences (caused by wind) between indoor and outdoor air; otherwise, the air exchange rate remains too low [30–33]. In contrast, air purifiers function effectively regardless of such conditions. Additionally, many rooms are equipped only with small upper windows, which may not provide sufficient airflow. Cross-ventilation, an especially effective method, requires windows on opposite walls, which are not always available. During the colder seasons, continuous window ventilation may not be suitable for several reasons [34–37]:

1. Room heaters are not designed to compensate for a constant supply of cold air.
2. It is both ecologically and economically unjustifiable, leading to higher heating costs and increased CO<sub>2</sub> emissions.
3. The convection of cold air within the room can negatively impact occupant comfort and well-being.
4. The supply of dry winter air can dry out mucous membranes, increasing human susceptibility to pathogens.
5. The reduced infection risk achieved through ventilation may be offset, as cold and dry air can enhance virus viability and transmission.

Mobile air purifiers often use high-efficiency particulate air (HEPA) filters, which effectively reduce concentrations of particulate matter and bioaerosols in the air. Some devices also utilize UV disinfection instead of particulate filters, aiming to inactivate viruses such as SARS-CoV-2 [38]. However, devices that rely on ozone or ionization to inactivate viruses are not recommended due to the potential health risks associated with ozone gas. Ozone can chemically react with other substances in the air, resulting in the formation of new pollutants [39].

There has been a significant surge in the availability of mobile air purifiers on the market. However, there are currently only a few regulations and standards for evaluating these devices. One commonly used evaluation method is the clean air delivery rate (CADR), defined by ANSI/AHAM [40]. CADR is measured in a predefined test room by comparing the natural decay rate of particle concentration (with the device OFF) to the active decay rate (with the device ON), based on the volume of the test room. In addition to ANSI/AHAM, several other international standards exist [41–47]. However, all of these standards focus on particle removal and do not specifically address bioaerosols [48].

The filtration behavior of bioaerosols may differ from that of other particulate matter, but this remains an open

question and is beyond the scope of this paper. Manufacturers typically report the volume flow rate of their air purifiers, which does not necessarily reflect the device's effective cleaning rate. Therefore, the current CADR estimation protocols require careful scrutiny, as certain steps may lead to falsely safe estimates. In this study, we first review existing CADR estimation protocols and identify the problematic aspects. We then propose modifications and introduce the *hygienic air delivery rate* (HADR), which provides a more accurate assessment of an air purifier's effective cleaning performance.

The main contributions of this work include identifying key limitations in the standard CADR testing protocol and quantifying its impact on the perceived performance of air purifiers. To address these shortcomings, we propose the HADR as a novel and more realistic alternative for measuring effective air purification. This proposal is supported by detailed simulation-based and experimental case studies comparing air volume ( $Q$ ) and HADR values across real-world devices. Furthermore, we offer design-oriented recommendations to enhance HADR performance through the optimization of nozzle geometry, device placement, and the incorporation of secondary flow mechanisms.

This paper is organized as follows: Section 2.1 presents a model for predicting infection risk in ventilated environments. Section 2.2 discusses CADR and its limitations, while Section 2.3 introduces HADR and outlines the corresponding protocol. Strategies for improving HADR are explored in Sections 2.4 and 2.5. Section 3 presents case studies of real devices, and finally, Section 4 summarizes the overall discussion.

## 2. Identification of Key Limitations in the Existing Testing Protocol

**2.1. Reduction in Infection Risk Through Ventilation.** In indoor environments, airborne pathogen-laden respiratory droplets can be generated through expiratory actions [7, 49]. These droplets play a key role in transmitting pathogens from an infected individual (the emitter) to a potential new host. The transmission risk of these aerosols can be reduced by ventilating the indoor space, which introduces fresh air from the outside and removes contaminated air (see Figure 1). Considering both emission and ventilation effects, Wells [50] and Riley et al. [51] developed a model—now known as the Wells–Riley model—to assess the risk of infection. The Wells–Riley equation is expressed as

$$P = \frac{N}{S} = 1 - e^{-I p q t / Q} \quad (1)$$

where  $P$  is the probability of infection,  $N$  is the number of infection cases,  $S$  is the number of susceptible individuals,  $I$  is the number of infectious individuals,  $p$  is the pulmonary ventilation rate of a person (typically measured in cubic meters/hour),  $q$  is the quanta generation rate (1/hour),  $t$  is the exposure time (hour), and  $Q$  is the room ventilation rate with clean air (cubic meters/hour). Thus, ventilation plays a crucial role in reducing the probability of infection transmission, which decays exponentially over time—as an increase in the fresh air supply rate  $Q$  lowers the risk of infection.

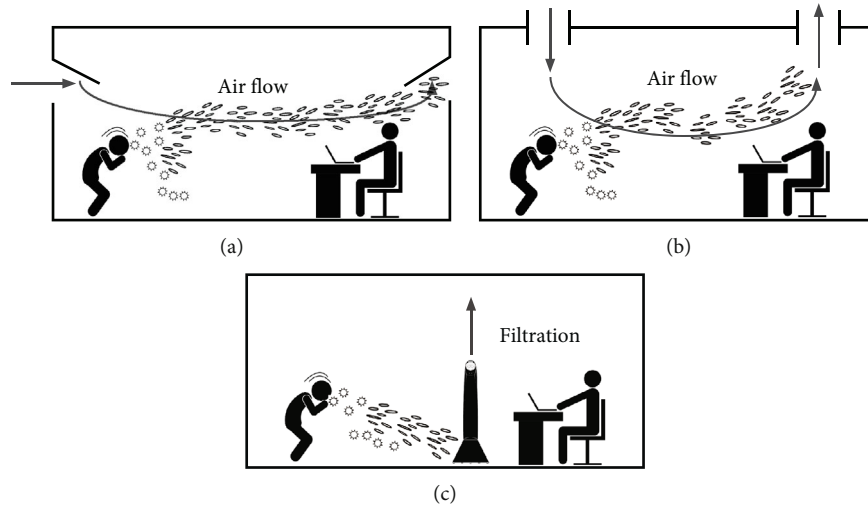


FIGURE 1: The contaminated indoor environment is cleaned (a) by ventilating outdoor air through windows, (b) by an HVAC system, and (c) by a mobile air purifier. The mobile air purifier does not introduce fresh air from outside; instead, it operates by drawing in indoor air, deactivating or filtering out aerosols, and then releasing purified air back into the room.

For practical purposes, maintaining a ventilation rate of 600–800 m<sup>3</sup>/h can reduce the potential risk to as low as 1% [52]. However, further increasing the ventilation rate may not yield significant additional benefits [30] and may simply lead to higher energy costs. Therefore, the ideal ventilation rate is generally maintained within the range of 600–800 m<sup>3</sup>/h. It is important to note that the ideal flow rate for ventilation is not necessarily the same as that for air purifiers, due to differences in flow behavior.

**2.2. CADR.** Mobile air purifiers operate differently from traditional ventilation systems, as they do not introduce fresh air from the surroundings. Instead, they draw in contaminated air from the room, deactivate or filter the aerosols, and then release the treated air back into the same space. The airflow characteristics also differ from those of ventilation systems, since both the intake and exhaust occur at the device itself. As a result, it is important to accurately measure the effective cleaning rate of air purifiers. Current international standards [40–47] primarily follow a protocol for estimating the CADR, measured in cubic meters/hour, which is defined as

$$\text{CADR} = V_R(k_a - k_n), \quad (2)$$

where  $V_R$  is the volume of the test room (cubic meter),  $k_a$  is the active decay rate (1/hour), and  $k_n$  is the natural decay rate (1/hour). The decay constants  $k_a$  and  $k_n$  are derived empirically by estimating the temporal concentration evolution as

$$C = C_0 e^{-kt}, \quad (3)$$

which results in the decay constant as

$$k = \frac{-\ln(C/C_0)}{\Delta t}, \quad (4)$$

where  $C_0$  is the concentration of particles (particles/cubic meter) at  $t=0$ ,  $C$  is the concentration (particles/cubic meter) at time  $t$ , and  $k$  is the decay rate (1/hour). Over time, the number of aerosols decreases due to natural decay. When the air purifier is turned on, the decay results from both natural processes and active deactivation by the device. Therefore, the decay rate attributable to the purifier is the active decay rate  $k_a$  minus the natural decay rate  $k_n$ .

During a typical test, a room with a 28-m<sup>3</sup> volume is used. The room is thoroughly cleaned before each test and standardized with specific surface specifications. To evaluate the device's filter performance, a precise amount of dust, pollen, or smoke particles is introduced into the room. After a 1-min settling period, the filter test begins. Particle concentration is then measured every minute for 20 s. Based on the experimental data, the CADR is estimated according to Equations (2)–(4). For meaningful comparisons between devices, CADR values are reported separately for the removal of dust, pollen, and smoke. These distinctions are necessary because air purifiers do not remove all particle types equally effectively, as particles vary in size and physical properties.

The CADR value is primarily used to estimate and compare the performance of air purifiers and is intended to reflect the effective room cleaning rate. However, purifier performance depends not only on the volume flow rate  $Q$  but also on the effectiveness of airflow across the room and the efficiency of aerosol deactivation. In CADR estimation protocols, a secondary mixing fan is operated within the test room to achieve a well-mixed air condition—likely

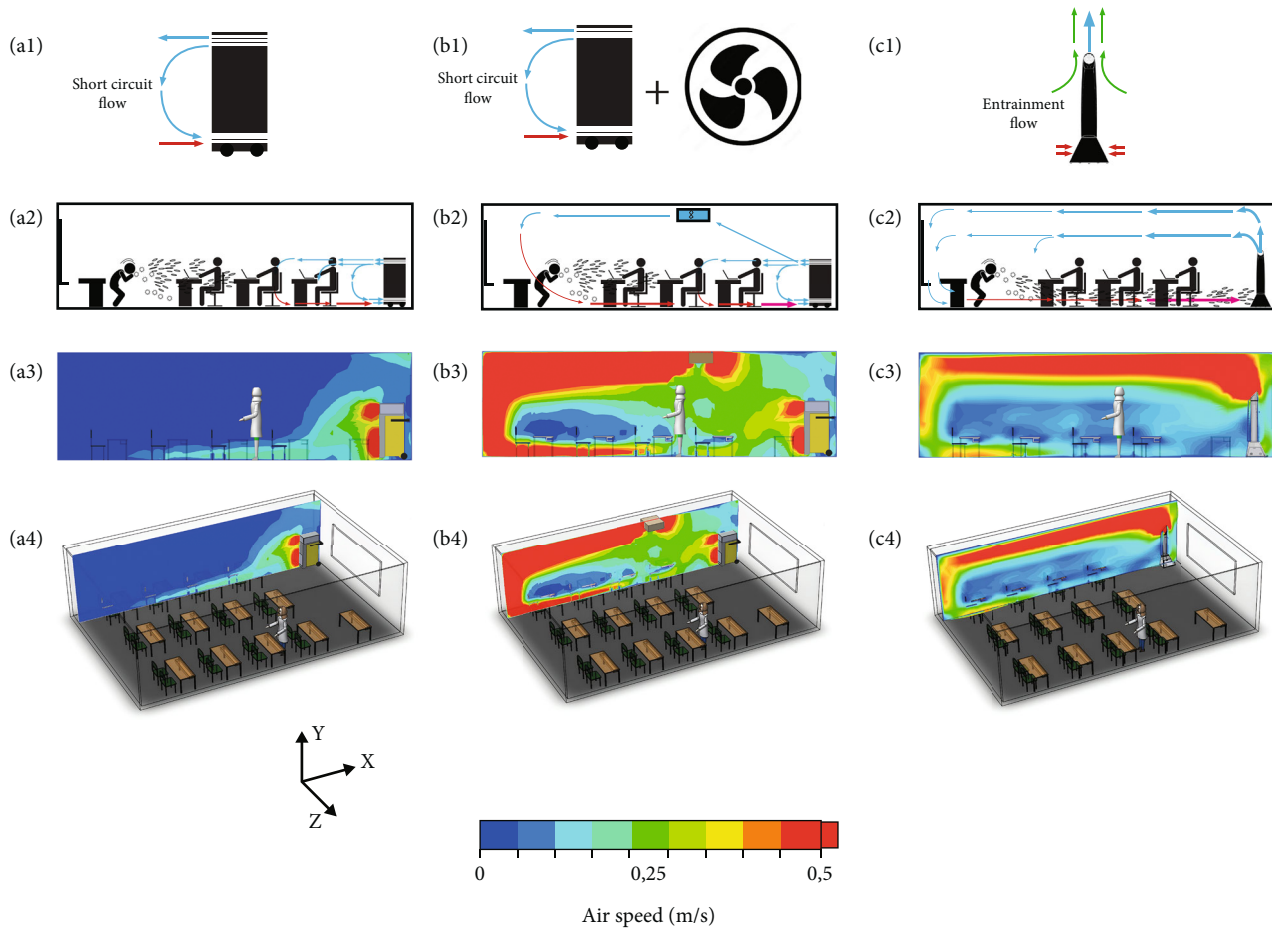


FIGURE 2: Air purifiers draw in contaminated air and release treated air back into the room. In one scenario (a1), a schematic illustrates an air purifier placed inside a room. However, this configuration (a2) fails to generate adequate circulation throughout the space. Simulation results (a3, a4) reveal that the air emitted by the purifier is quickly recirculated back into the device itself, rather than reaching the rest of the room. The purifier in this setup operates at a volume flow rate of  $1200 \text{ m}^3/\text{h}$ , and the room used in this and all subsequent simulations has dimensions of  $9 \times 6 \times 2.75 \text{ m}$ . To estimate the CADR according to standard protocol, an additional fan is introduced, as shown in schematic (b1). This setup (b2) significantly enhances air circulation within the room. The simulated air speed (b3, b4) confirms that the fan assists the purifier in creating circulation zones, enabling the treated air to reach all areas of the space. In this case, the purifier and the fan operate at volume flow rates of  $1200$  and  $2000 \text{ m}^3/\text{h}$  (free blowing), respectively. An improved purifier design is shown in schematic (c1), featuring a smaller exit nozzle and better alignment. This optimized configuration (c2) achieves sufficient air circulation and efficiently cleans the room. The simulation results (c3, c4) demonstrate that the improved purifier can circulate air effectively even with a significantly lower flow rate of  $450 \text{ m}^3/\text{h}$ —compared to the original configuration in (a), which required  $1200 \text{ m}^3/\text{h}$  and still failed to deliver full-room coverage.

introduced to align with the assumptions in the Wells–Riley model [50, 51]. While adding a fan may be appropriate for estimating ventilation effectiveness, it may distort the performance evaluation of air purifiers, whose efficiency strongly depends on specific flow conditions [52, 53]. An additional fan can artificially enhance the purifier’s performance by improving airflow circulation [54] (see Figure 2a,b). As a result, the CADR test may yield overly optimistic results, making the inclusion of a mixing fan in the protocol questionable.

To demonstrate the impact of an additional fan, realistic room scenarios were numerically simulated using the commercial software SOLIDWORKS Flow Simulation [55]. The computational domain dimensions were  $9 \times 6 \times 2.75 \text{ m}$ , with no-slip and no-penetration boundary conditions

applied to the room’s walls and to the surfaces of objects within the room (see Figure 2). Volumetric flow rates were assigned at the inlet and outlet corresponding to the air purifier and the fan. SOLIDWORKS employs the finite volume method (FVM) to solve the mass and momentum conservation equations. Temperature was assumed to be uniform and constant, with air properties set to those at  $20^\circ\text{C}$ . An initial pressure of 1 bar was assumed, and simulations were run until a steady state was reached. The domain was initially discretized into a grid of  $22 \times 6 \times 16$ , with adaptive meshing used to refine complex regions and ensure convergence and accuracy.

In the real-life scenario illustrated in Figure 2a, the air purifier alone fails to achieve sufficient air circulation across the room. However, in the standardized CADR test setup

using an additional fan (Figure 2b), circulation is significantly enhanced. This leads to an apparent increase in cleaning efficiency. In practice, however (as shown in Figure 2a), the air purifier's performance would be substantially lower. Consequently, CADR may overestimate purifier performance and result in misleading, falsely safe conclusions.

Other factors—such as heat convection, flow obstructions, the positioning of the purifier, and the alignment of the device within the test room or the position of the outlet and inlet grills toward each other—also play a crucial role in influencing airflow behavior [56, 57]. Therefore, these variables must be standardized during testing. Notably, the CADR does not provide insight into filter performance for fine dust or VOCs, nor does it indicate the specific concentration of filtered or deactivated pathogen-laden aerosols.

As a result, the current CADR testing protocol must be revised to address potential sources of false safety, such as the use of additional mixing fans, the limited volume of small test chambers, and various factors that influence flow characteristics. During the pandemic, several task forces—such as the German DIN FNL7 commission—focused on developing mitigation strategies for controlling bioaerosols using mobile air cleaners, particularly those employing UV-C technology. In the course of their work, they identified these CADR shortcomings and, in their technical specification paper (DIN TS 67506) [58], proposed the development of a revised test protocol. This protocol should address the previously mentioned limitations and place equal emphasis on bioaerosols, as is already done for dust, smoke, and pollen. The German standard VDI 4300 [59] adopted these recommendations, and new standards have since been introduced. However, these updates have not yet been widely disseminated and remain under further development. The resulting standard is known as the HADR, which will be explained in the next subsection.

**2.3. HADR.** The HADR is introduced as a more realistic and safety-conscious metric for evaluating the effective performance of mobile air purifiers. Unlike conventional testing protocols, the HADR measurement excludes the use of auxiliary mixing fans during the device's operation, ensuring that the observed performance reflects only the purifier's actual airflow and filtration capabilities. While the mathematical formulation of HADR is similar to that of the CADR, the testing protocol for HADR is fundamentally different. It requires that manufacturers specify installation parameters such as the orientation of the emitter nozzle, device placement, and consideration of real-world obstructions (e.g., furniture), temperature gradients, and typical human occupancy. As a result, HADR values are more directly applicable for practical assessments such as determining the number of purifiers needed in space or estimating infection risk using models like Wells–Riley.

**2.3.1. Difference Between CADR and HADR.** The key difference between CADR and HADR lies in the testing environment and the assumptions behind the performance evaluation. CADR is measured under idealized laboratory conditions, often with a secondary mixing fan that promotes

uniform air distribution and can unintentionally support the purifier's circulation, thus inflating performance results. This artificial setup may simplify testing but can create a false sense of safety when applied to real-world environments. In contrast, HADR eliminates these artificially enhanced conditions and more accurately represents typical indoor scenarios where no external mixing exists. Furthermore, CADR primarily focuses on general particle removal (such as dust, smoke, or pollen), whereas HADR is motivated by the need to address bioaerosol mitigation—a crucial consideration in contexts involving airborne infectious disease transmission. Consequently, HADR serves as a more conservative and reliable metric for both consumers and policymakers when comparing the true effectiveness of air purification devices.

**2.3.2. Derivation of HADR.** We assume that the room is well mixed with concentration  $C_0$  before the purifier starts, and we neglect any infiltration. The conservation equation reads

$$V_R \frac{dC}{dt} = QC_{in} - QC_{out}, \quad (5)$$

where  $Q$  is the volume flow rate of the air purifier (cubic meters/hour),  $C_{in}$  is concentration of inlet air (particles/cubic meter), and  $C_{out}$  is the concentration of the air flowing out. We assume no leakage and perfect filtration; thus,  $C_{in} = 0$ . Furthermore,  $C_{out} = C$ , assuming that the air inside is homogeneously mixed. This differential equation can easily be integrated, resulting in

$$C = C_0 e^{-Q\Delta t/V_R}, \quad (6)$$

with the decay rate

$$k_a = \frac{Q}{V_R} = \frac{-\ln(C/C_0)}{\Delta t}. \quad (7)$$

The aerosols sediment with time naturally under the effect of gravity. The decay rate of concentration is thus assessed by turning off the air purifier as

$$k_n = \frac{-\ln(C_n/C_0)}{\Delta t}. \quad (8)$$

Since the HADR describes the effect only due to the air purifier device, the natural decay rate is deducted from the active rate, and the equation for HADR then reads

$$\text{HADR} = Q_{\text{active}} - Q_{\text{natural}} = V_R(k_a - k_n). \quad (9)$$

The equation for the estimation of HADR thus looks similar to that of CADR shown in Equation (2); however, the protocol differs significantly. For the estimation of HADR, the external fan remains switched off, and only the air purifier forces the flow inside the room. However, for the estimation of the concentration  $C$  at time  $t$  after the air purifier is switched off, the room should be mixed well to ensure that the concentration  $C$  is an averaged estimate of the room and is not prone to nonuniformity.

**2.3.3. HADR Measurement Protocol.** The test procedure should be based on DIN EN ISO 16000 Part 9 [60] and DIN ISO 16000 Part 36 [61]. These international standards define a general laboratory test method for determining the area-specific emission rate of VOCs from newly manufactured building products or furnishings under controlled climate conditions [60], as well as a standardized method for assessing the reduction rate of culturable airborne bacteria by air purifiers using a test chamber [61].

When testing larger air purifiers (with airflow rates exceeding  $300 \text{ m}^3/\text{h}$ ) or conducting measurements involving bacteriophages, both the testing procedures and the room size must be adapted accordingly. The test conditions and the results obtained must be transferable to real-world operating environments. Additional international standards [40, 53, 62] are also available for testing air purifiers with various microorganisms and may serve as valuable references when developing the final test protocol, if needed.

1. Determine the natural decay rate of aerosol concentration in the room without operating the air purifier:
  - a. Nebulize aerosols according to predefined quality and quantity characteristics, as specified in DIN ISO 16000 Part 36 [61].
  - b. Use an additional mixing fan during the aerosol nebulization to ensure homogeneous distribution throughout the room.
  - c. Stop nebulization once the predetermined volume of liquid has been fully dispersed.
  - d. Determine the initial concentration  $C_0$  by averaging concentration values measured at several locations in the room. The room is considered well mixed if the deviation at different locations from the average is less than 10%.
  - e. Allow the room to sit undisturbed for 30 min to permit natural sedimentation.
  - f. After 30 min, briefly turn the mixing fan back on for 1 min to rehomogenize the aerosol concentration.
  - g. Perform a second sampling at the same measurement points to determine the natural reduction in concentration by comparing  $C_0$  with the new concentration data  $C_n$ .
2. Determine the active decay rate of aerosol concentration with the air purifier in operation:
  - a. Prepare the room for the second series of measurements by nebulizing new aerosols according to predefined quality and quantity characteristics, as specified in DIN ISO 16000-36 [61].
  - b. Use an additional mixing fan during the nebulization to achieve a homogeneous distribution of aerosols throughout the room.

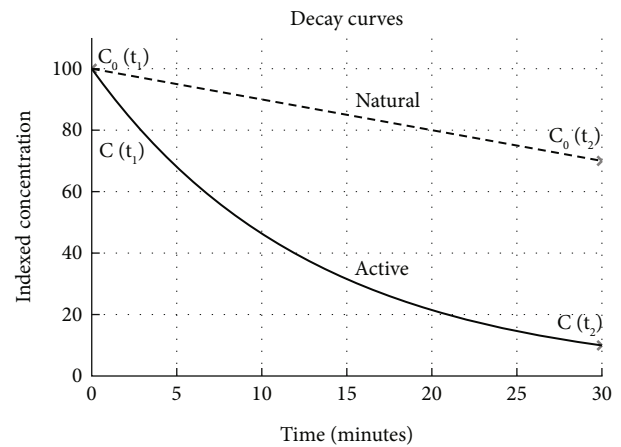


FIGURE 3: The decay curves for natural and active conditions, showing a significantly faster reduction in indexed concentration under active conditions compared to natural decay (adapted from VDI 4300 B14 2024).

- c. Determine the initial concentration  $C_0$  by averaging concentration values measured at several locations in the room. The room is considered well mixed if the deviation from the average at different locations is less than 10%.
- d. Switch on the air purifier and operate it for 30 min without any additional influence on the room's airflow.
- e. After 30 min, switch off the air purifier and run the mixing fan for 1 min to rehomogenize the air in the test room.
- f. Perform a second sampling at the same measurement points to determine the active concentration reduction by comparing  $C_0$  with the new concentration data  $C_a$  (Figure 3).

**2.4. Adding Shear Effects in the Flow to Increase the HADR.** In an air purifier, air exits through a nozzle, which is assumed here to be circular with radius  $R_0$ . As the air exits the nozzle, the locally increased velocity entrains surrounding air into the emerging jet due to shear and viscous effects, resulting in an increase in the volume flow rate with axial distance from the nozzle. This system can be analytically described (see the textbook by Schlichting [63]) by conserving momentum flux and assuming an axisymmetric jet emerging from a point source. The same scaling behavior was later confirmed by experimental studies [64] and is expressed as

$$Q(x) \sim \frac{Q_0}{R_0} x, \text{ for } x \gg R_0, \quad (10)$$

where  $Q(x)$  is the volume flow rate at a generic axial distance  $x$  from the nozzle,  $Q_0$  is the initial volume flux, and  $R_0$  is the nozzle radius; see Figure 4. The volume flow rate  $Q(x) = 2\pi \int_0^\infty v(r, x) r dr$  increases with distance  $x$  due to dragging along

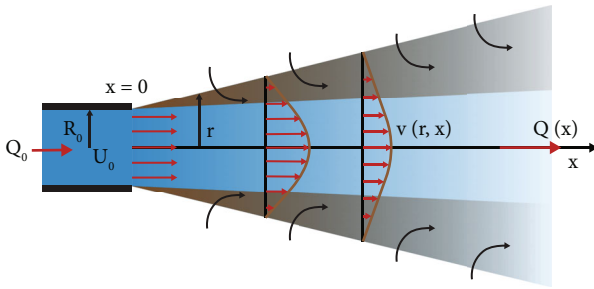


FIGURE 4: As the air flows outside the nozzle, the air jet entrains air from the surroundings due to the viscous effects. The momentum of the jet is assumed to remain constant in the flow direction; however, as the area of the air jet increases, the average jet velocity decreases. A larger flow rate  $Q_0$  increases the volume entrained into through shear effects.

the surrounding air. Furthermore, the volume flow rate at any distance  $x \gg R_0$  from the nozzle linearly increases with the initial volume flux  $Q_0$  and decreases with the nozzle radius  $R_0$ .

For air purifiers, the aim is to enhance the entrainment of surrounding air and thus maximize  $Q$  as much as possible. To achieve this, the initial volume flux  $Q_0$  should be increased. Obviously, there are limitations, considering electrical power consumption, and therefore, it is kept in the range of 600–800 m<sup>3</sup>/h. In contrast, reducing the nozzle radius  $R_0$  increases the  $Q$  without this issue. The radius of the nozzle should be kept as small as possible. However, if  $R_0$  is too small, the air jet velocity will be very high, and such a high air jet speed might cause discomfort to the people in the room. Another issue could be the increase in the noise of the purifier. Thus, the initial volume flux  $Q_0$  should be kept large, and the nozzle radius  $R_0$  should be kept as small as possible considering the constraints of electrical power usage and human discomfort due to high air speed and noise.

**2.5. Additional Considerations to Enhance the HADR.** The HADR reflects the effective cleaning of the room, with higher values being desirable. The ratio of HADR with volume flow rate  $Q$ , that is, HADR/ $Q$ , indicates the effective room cleaning for a given volume flow rate  $Q$ . This ratio is less than one, and one should ideally create conditions to maximize this ratio. A large HADR/ $Q$  ratio suggests that the air flowing out is mixing well with the surrounding air, good air circulation is maintained, and short circulations have been prevented; see Figure 2c.

A common issue encountered with air purifiers is short circulation, as illustrated in Figure 2a. However, even for simulation with a smaller flow rate (450 m<sup>3</sup>/h), enhancing the nozzle alignment and reducing the exhaust nozzle's area lead to adequate circulation, as shown in Figure 2c. This result highlights the importance of these additional considerations. To prevent inadequate short circulation, the following aspects should be improved:

1. The alignment of the exit nozzle should be away from the inlet of the device.

2. The device should be placed in the room such that the hindrance of outflowing air is minimal by the surrounding walls, furnishing, curtains, etc.
3. The grills should be designed to avoid short recirculation.
4. Secondary flow could be produced to support the purifier in circulating the air across the whole room. Such secondary flows could be created by means of additional fans or temperature gradients due to heaters or air conditioners.
5. The air exhaust grills, housing, and air inlet grills can be designed in such a way that entrainment flows can be optimized.

As discussed in Section 2.4, larger initial volume flow rates are desirable for achieving a high HADR. Beyond electrical power consumption, additional factors may also limit the maximum volume flow rate  $Q$ . For example, mechanical (HEPA) filters require low airspeeds to ensure effective filtration [65]. As a result, HEPA filter-based devices typically operate at lower velocities and require large surface areas, such as wide grills.

Devices that utilize UV chambers may also face limitations on the maximum achievable flow rate  $Q$ . A minimum dwell time is necessary for the air to be effectively treated within the UV chamber, as sufficient UV light intensity must be maintained to deactivate bioaerosols [65–67]. For instance, regulatory bodies recommend a high intensity of approximately 100 J/m<sup>2</sup> to adequately deactivate viruses like SARS-CoV-2 [67]. These intensity requirements can be met by reducing airflow in a low-powered UV unit, but this also limits the maximum  $Q$ .

One potential solution is to incorporate a parallel flow configuration, allowing the device to operate at a higher  $Q$  while maintaining the required dwell time. This approach can achieve a higher HADR without compromising the effectiveness of aerosol deactivation.

### 3. HADR in Practice: Case Studies

The legitimacy of HADR is best demonstrated through practical case studies. The primary objective of HADR, compared to CADR, is to prevent a false sense of safety and to assist consumers in selecting the most appropriate devices. Manufacturers often advertise the maximum airflow capacity of their devices without highlighting the internal pressure drop caused by the filter system. Even devices tested according to DIN EN ISO 5801 typically do not report the effective cleaning ratio, represented by the HADR-to- $Q$  ratio (HADR/ $Q$ ).

Relying solely on a device's advertised airflow capacity can be misleading, as the actual HADR may be significantly lower. Table 1 provides an overview of case reports from well-known, commercially available devices. For each case, the HADR is calculated, and the percentage ratio of HADR to  $Q$  is presented. It is evident that this percentage is low for most devices.

TABLE 1: Overview of reviewed devices and their derived and compared HADR values.

Devices	Q (m <sup>3</sup> /h)	V <sub>R</sub> (m <sup>3</sup> )	CADR (m <sup>3</sup> /h) <sup>a</sup>	HADR (m <sup>3</sup> /h)	HADR/Q (%)
Trotec TAC V+ [15]	1200	200	n.a.	761	63%
Deconta PLR Silent R150 [68]	1062	127	n.a.	300	28%
VB Steribase 450 [69]	450 <sup>b</sup>	127	n.a.	652	145%
M&H OurAir TK850 (US) [70]	770	103	n.a.	418	54%
M&H OurAir TK850 (EU) [70]	950	222	n.a.	385	41%
M&H OurAir SQ2500 [70]	2500	268	n.a.	1415	57%
PlasmaMade AAC37170 [71]	400	24	n.a.	294	74%
Airdog X8 [72]	1000	75	798	44	4.4%

<sup>a</sup>In most cases, the CADR equals 90%–100% of Q due to the supportive effect of an additional mixing fan. CADR was not available because tests were done with biological contaminants, which are out of the standard CADR testing scope.

<sup>b</sup>This device added volume flows through entrained shear effects, increasing real Q to 756 m<sup>3</sup>/h which to HADR result is 86%, but the device Q compared to the HADR yields 145%.

Evaluating a device's performance based only on its air-flow capacity may lead to false conclusions. Instead, devices should be assessed and compared based on their estimated HADR values, which offer a more accurate representation of their true air-cleaning effectiveness.

#### 4. Conclusion and Discussion

Most indoor environments are cleaned through ventilation and HVAC systems; however, air purifiers can also be used effectively. Manufacturers typically provide only the device's volume flow rate. While some protocols exist to assess the performance of air purifiers—such as those used to evaluate the CADR—one key step in the CADR estimation process involves switching on an additional fan during the operation of the air purifier to achieve a well-mixed room. As discussed earlier, this additional fan can alter the flow characteristics of the air purifier, and therefore, it should not be active during the purifier's operation.

However, the well-mixed condition can still be achieved after the air purifier runs by briefly operating the mixing fan. The effective output from this revised protocol is referred to as the HADR.

To achieve high HADR values, the volume flow rate Q should be maximized and the exit nozzle radius R<sub>0</sub> minimized—within the constraints imposed by power consumption, noise levels, filtration efficiency, and/or required UV exposure time. In addition, the alignment and positioning of the device, as well as potential obstructions within the room, must be properly considered. Secondary flows—generated either by an auxiliary fan or by temperature gradients from heaters or air conditioners—can further improve HADR.

Finally, case studies of real devices are presented, including their reported volume flow rate Q and measured HADR. These studies demonstrate that the effective cleaning rate (HADR) can be significantly lower than the volume flow rate Q. Therefore, HADR, rather than CADR or raw flow rate alone, should be used as the key metric for assessing and comparing air purifiers.

While the introduction of HADR offers a promising step toward a more realistic evaluation of air purifiers, several

open challenges remain. A key limitation lies in the broader implementation of HADR in commercial testing environments, which requires updated protocols, standardization across manufacturers, and regulatory alignment. Additionally, the current formulation of HADR focuses on generic bioaerosol inactivation/removal.

Future work should extend the metric also to account for specific particle removal. Another avenue lies in the potential integration of HADR-based performance feedback with smart HVAC systems, enabling adaptive ventilation strategies that respond to real-time indoor air quality conditions. Finally, practical trade-offs must be further studied—particularly the balance between maximizing airspeed and HADR while minimizing noise levels and power consumption, which are crucial for user comfort and energy efficiency. Addressing these aspects will help ensure that HADR evolves into a widely adopted and versatile standard for assessing indoor air purification.

#### Data Availability Statement

Data are available on request from the authors.

#### Conflicts of Interest

Fahmi Yigit is the CTO of Virobuster International GmbH, a company that supplies and installs hygienic ventilation systems. All other authors report no conflict of interest relevant to this article.

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