# Is building ventilation a process of diluting contaminants or delivering clean air?

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## Abstract

The purpose of the paper is to discuss the performance of air distribution systems intended for dilution of contaminants (e.g., mixing ventilation) and those intended for delivery of clean air to local regions within rooms (e.g., personalized ventilation). We first start by distinguishing the systems by their visiting frequency behaviour. Then, the performance of the systems with respect to their possibility to influence contaminant concentration in the room or region is dealt with. Dilution capacity concept for mixing systems is discussed and delivery capacity concept for systems intended to deliver clean air locally is introduced. Various ways for supply of clean air to regions within a room are presented and their pros and cons are discussed. In delivery capacity systems the most important single parameter is the entrainment of ambient air into the primary supply flow. Therefore, methods of determining entrainment in these systems needs to be defined and the results should be included when describing the performance of the air terminal devices.

**Keywords**: probability to return, visitation frequency, dilution capacity, delivery capacity, entrainment, entrainment mixing factor

## Introduction

Traditionally, an air distribution system serving a whole room, often referred to as total volume air distribution (TVAD) system, is viewed as a system where the supplied flow rate provides a dilution capacity that lowers contaminant concentrations generated in the room.[1] The primary aim is to provide and maintain uniform indoor climatic conditions (temperature, velocity and contaminant concentration) at levels deemed acceptable for an 'average occupant'. During the last decade, there has been emphasis on systems that are marked as delivering clean air to microclimate regions within a room, referred to herein as delivery capacity systems, an example is personalized ventilation systems.[2] Optimal performance of dilution capacity is obtained with a large entrainment which contrasts with delivery capacity systems that require low entrainment for optimal delivery of clean air, as will be discussed herein. This calls for the need to introduce concepts that discriminate between performances of different types of air distribution systems (low Vs. high entrainment requirements). We hope that this paper will contribute to introduce a fruitful discussion on local delivery of supply air.

## Basic concepts charachterizing air distribution - driving flow

### *Return probability, visitation frequency and two population fluid*

Generally, the flow in a room has a recirculation and the contaminant distribution is not always uniform.[3] Therefore, contaminants and air leaving a region, such as an occupied region or breathing zone, may return and pass through the same region once more or several times, see Figure 1 ($\dot{m}$ is the generation rate of a contaminant and $q_v$ is the ventilation flow rate). The probability to return is $r$ and subsequently the probability to leave for never returning is $1 - r$.[4] The corresponding flow rates associated with these probabilities are given in Table 1. Thus, air in a ventilated room is a two-population fluid, one population returning and one leaving for never returning. The measuring methods used within fluid mechanics cannot discriminate between the two populations. Only tracer gas technique can discriminate between the populations, because it reacts to dilution which is the property associated with the population leaving for never returning.

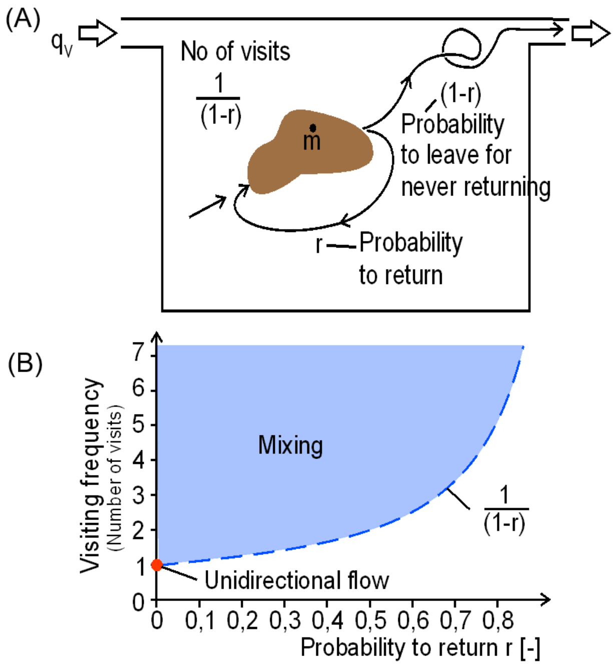


Figure 1. (A) Definition of probabilities; (B) Visiting frequency and probability to return

Table 1 Probabilities and associated flow rates

| Probability | Notation | Corresponding flow rate | Magnitude |
|---|---|---|---|
| Probability to return | $r$ | Recirculating flow rate | Any |
| Probability to leave for never returning | $(1-r)$ | Purging flow rate | $\leq q_v$ |

Visitation frequency represents the number of times a particle and/or contaminant enters a local region and passes through it [5] and this is expressed in terms of the return probability [4] as

$$\text{Visitation frequency} = \frac{\mathbf{1}}{(\mathbf{1}-\boldsymbol{r})} \quad (1)$$

When the probability to return is zero the visitation frequency is equal to one and in other cases it is larger so there is more than one visit e.g., mixing ventilation systems. In view of the total room flow field, a lower value of an average visitation frequency indicates good ventilation of the local region because few contaminants return to the region.[5] This leads to the following natural classification of air distribution systems: Systems with the probability to return equal to zero are systems with unidirectional flow and the other systems are mixing or dilution systems. Subsequently, mixing in a room in the context of ventilation means that the air and/or the contaminant returns to the local region at least once or several times.

### ***Driving flow and entrainment mixing factor***

The driving flow is the flow element controlling the airflow in a ventilated room. This concept is introduced because the driving flow does not need to be the ventilation flow rate. It may be generated by a buoyancy source (heat source) with zero flow and subsequently zero momentum at the starting point. Examples of such flows are plumes from buoyancy sources or the boundary layer flow along surfaces with heat transfer. An example of a ventilation system where the driving flow is not the ventilation flow rate is displacement ventilation.[1] The flow elements controlling the airflow in a room interact with the surrounding air by entrainment.

The entrained flow rate, $Q_e(x)$, along the distance between the starting point to the location x from the supply is defined by

$$Q_e(x) = Q_x - Q_0 \tag{2}$$

Where ($Q_0$) and ($Q_x$) are the corresponding flow rates at the supply and point x downstream, respectively. The mixing factor due to entrainment at location x is defined as the amount of ambient air entrained at position x divided by the volumetric flow rate, $Q_x$, at position x.

$$\text{Mix}_{\text{Entrain}}(x) = Q_e(x)/ Q_x = (1- Q_0/Q_x) \tag{3}$$

The entrainment mixing factor gives a global measure of the mixing between the whole jet and the ambient fluid i.e., it gives the ratio of room air or contaminants entrained into a driving flow. With increasing distance, the fraction of entrained air increases and the theoretical limit of the mixing factor is 1, see Figure 2. In cases were the driving flow is starting from zero (plume), air in the flow consists from the very beginning of entrained air, see Figure 5, then $Q_e(x) = Q_x$ and $\text{Mix}_{\text{Entrain}}(x) = Q_x / Q_x = 1$. The range of the mixing factor is $0 \leq \text{Mix}_{\text{Entrain}}(x) \leq 1$. $\text{Mix}_{\text{Entrain}}(x) = 0$ is the ideal condition for delivery capacity systems while $\text{Mix}_{\text{Entrain}}(x) = 1$ is for mixing systems.

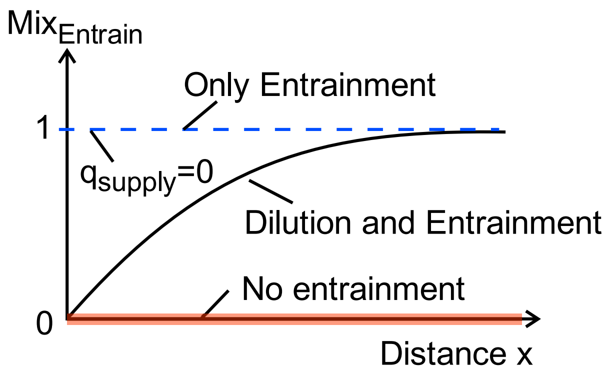


Figure 2. The mixing factor due to entrainment as a function of downstream distance

## Air distribution systems

### *Mixing systems and their dilution capacity*

Figure 3 illustrates a typical air distribution system for mixing ventilation. Due to entrainment, an internal flow rate larger than the ventilation flow rate is setup. The air flow dynamics are that air within the room must queue before it can leave the room through the extract air terminal. The queueing is manifested in such a way that the air goes around several times within the room before it leaves. As exemplified, the air has a visitation frequency of 4 in the indicated local region before leaving the room. Therefore, according to Equation 1 the probability to return ($r$) = 0.75.

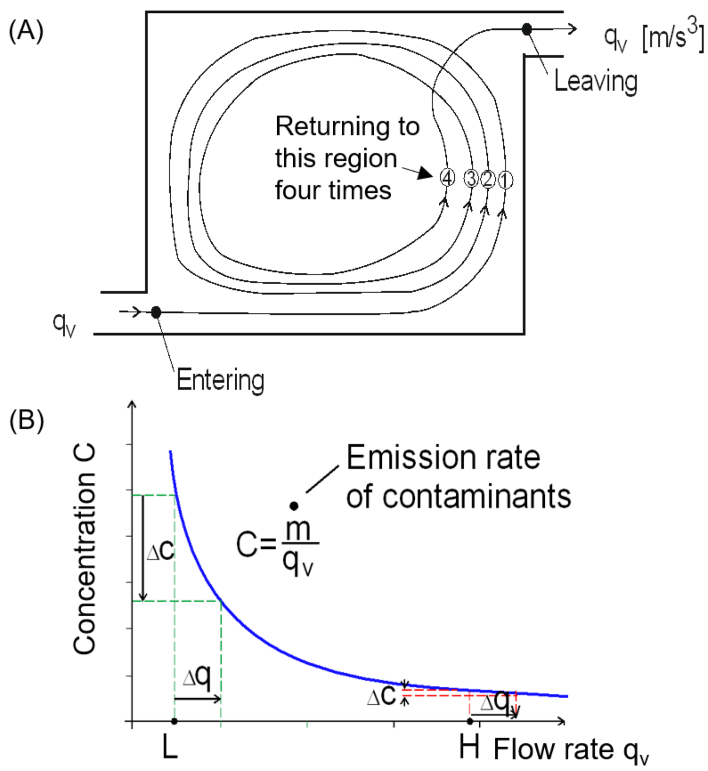


Figure 3. (A) Archetype of a mixing system; (B) Dilution curve (L: Low flow rate H: High flow rate)

If within the room there is a pollution source with an emission rate ($\dot{m}$) of contaminants. The concentration of the contaminants in the room will be defined by the dilution curve in relation to ventilation flow rate as illustrated in Figure 3B. The dilution curve highlights the fact that ventilation at conditions indicated by L is very important. A small increase in the ventilation flow rate ($\Delta q$) significantly reduces the concentration and vice versa i.e., a small reduction in flow rate increases the concentration drastically. On the other hand, at condition H an increase in the flow rate only marginally decreases the concentration and vice versa. A detailed discussion is presented by Sandberg. [6]

***Air distribution systems for supply of clean air within a zone in a room***

Figure 4 shows the air distribution systems that are generating a unidirectional flow at the beginning. Case A show a standard jet supply with a small core region (region downstream were supply conditions are sustained). In this paper, the region with supply air conditions is called the core region, henceforth. One possibility to expand the core region is to supply air over the whole floor area through nozzles with the aim to prevent entrainment into the supply air, see Case B. However, the lack of entrainment keeps the flow rate constant which gives rise to an adverse pressure gradient, a well-known "trouble maker" in fluid mechanics.[7] Thus, the velocity in the flow stream decreases due to the expansion of the cross-sectional area of the airflow from the total area of the nozzles $A_{nozzle}$ to the area of the room $A_{room}$.[8] This decrease is compensated by an increase in pressure Δp (ρ is the density of air) [1] expressed as,

$$\Delta p = \rho (q_v)^2 (\frac{A_{room} - A_{Nozzle}}{A_{room} A_{Nozzle}}) \tag{4}$$

This causes an unstable air distribution in the room which may result in supply air being focused to smaller regions (break through), a well-known phenomenon from supplying with perforated ceilings.[9] The remedy for this is shown in Case C, where entrainment is made possible by supplying over an area less than the floor area.[10] Case D is displacement ventilation where the air is driven by a plume from a heat source. Now the core region is extended to the height where the flow rate in the driving flow ($q_p$) is equal to the supply flow rate ($q_v$) of ventilation air.[1] Finally, Case E is where the supply of air is close to the target with a separation distance (s), which is the idea behind personalized or personal ventilation systems.[2,11] The separation distance is critical as it relates to how much ambient air entrains the jet flow, as will be discussed latter.

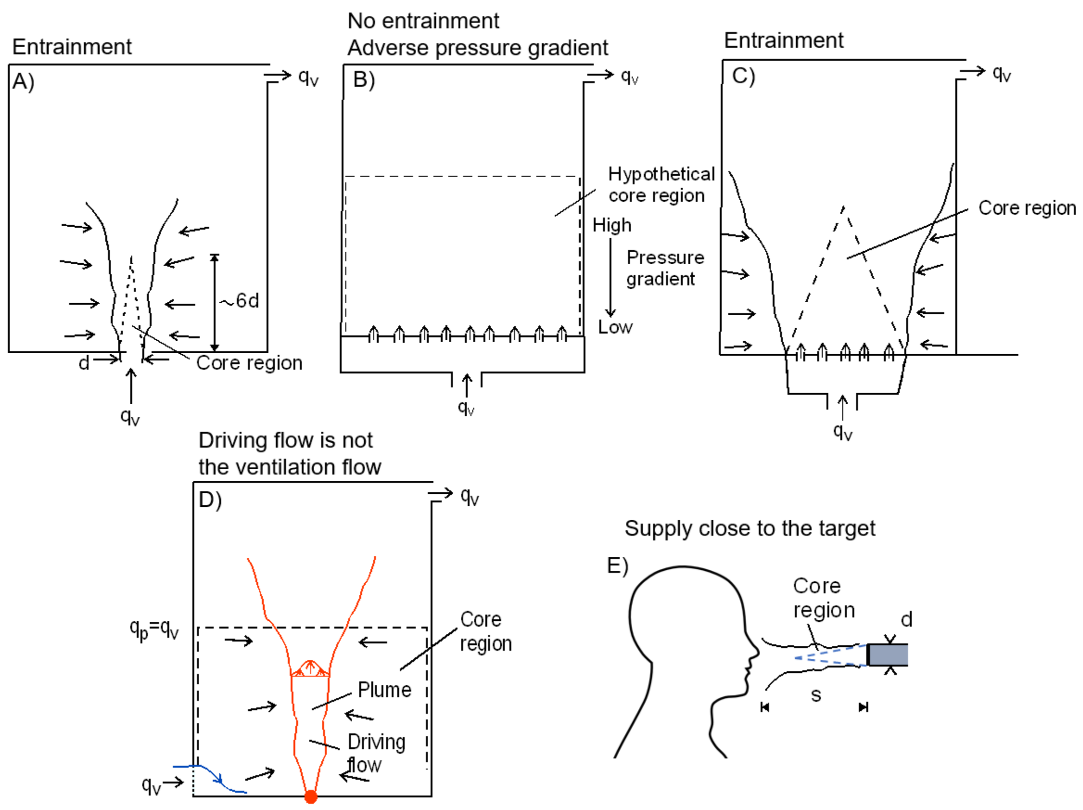


Figure 4. Direct supply of clean air: (A-D) expanding the core region; E) Supply close to the target

It is important to note that the systems in Figure 4 also have a dilution capacity for some contaminant sources. For example, displacement ventilation has a dilution capacity for sources located within the driving flow because ambient ventilation air is entrained into the driving flow, as demonstrated in Figure 5, consequently diluting the flow as the mixing effect is introduced between the two fluids.

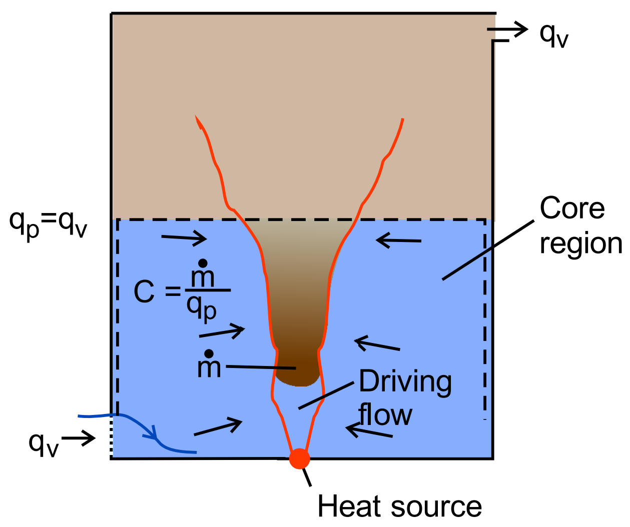

Figure 5. Due to entrainment of ambient ventilation air the dilution capacity is equal to the flow rate $q_p$ in the plume

### *Delivery capacity of clean air*

Figure 6 show a setup with a jet supplying clean air in a polluted room with a uniform ambient concentration ($C_{Amb}$). A natural question to ask is; how clean is the air when it arrives at the target (a specified point downstream)? This question can be answered by introducing the concept of delivery capacity and explore the resulting concentration at the target point. One way of defining the delivery capacity is to state the distance to the end of the core region or alternatively give the ratio or percentage of supply conditions present at the delivery point.

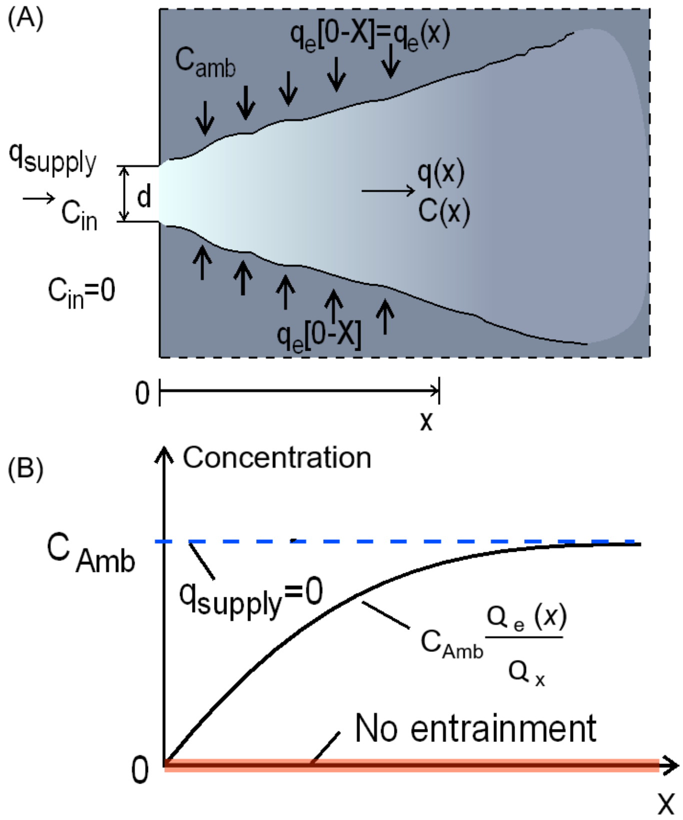


Figure 6. (A) Supply of clean air, $C_{in} = 0$, into a room filled with a pollutant of uniform concentration; (B) Entrainment mixing curve between the jet stream and ambient

At distance x we have the mass flow balance

$$Q_e(x)C_{Amb} = (Q_x - Q_0)C_{Amb} = Q_xC(x) \quad (5)$$

Which gives the concentration in the air stream,

$$C(x) = C_{Amb} * Mix_{Entrain}(x) = C_{Amb}\frac{Q_e(x)}{Q_x} \quad (6)$$

Clearly, the concentration in the supply air stream is controlled by the entrainment mixing curve defined by the ratio ($Q_e(x)/Q_x$), see Figure 6B. This contrasts with mixing systems where the concentration is controlled by the supply flow rate ($q_v$) governed by the dilution curve in Figure 3B. Therefore, in delivery capacity systems the only way to improve the situation is to reduce the entrainment. The delivery capacity is then defined herein as a fraction of the supply conditions delivered at a specific point downstream. For example, one would say a personalized air terminal device has a delivery capacity of 50 % at a downstream distance of 8d (where d = diameter of the supply nozzle), meaning 50% of the supply conditions are present and 50% are entrained contaminants at the defined downstream distance. Alternatively, delivery capacity can be presented as a function of the downstream distance for specific initial conditions.

## General discussion

The common ventilation systems, i.e. mixing and displacement, used in the built environment today are based on dilution air distribution principles. The governing principles are extensively researched and documented, and system performance testing methods are well grounded.[1,12–15] The disadvantage of dilution systems is that contaminants are also diluted and distributed in the room, which facilitates transport of pollution within the room and increases complaints of air quality, sick building syndrome and exposure to airborne infections.[16,17] The only way to alleviate this in dilution systems is to increase the supply flow rates [18] which consequently increases building energy use. An alternative solution is to employ microclimate ventilation systems like personalized ventilation that apply delivery capacity principles of air distribution. For a detailed discussion of delivery capacity systems, e.g., personalized ventilation refer to Melikov [2,11].

A lot of empirical studies have been done on delivery capacity air distribution systems, involving variations of air distribution devices mostly with free jets, and the results point to delivery of good ventilation in breathing zones. While there is a substantial body of literature, the influence of contaminant entrainment in supply jet flows and its implications on the delivery of supplied air is not fully addressed. Entrainment in delivery capacity distribution systems occurs in two phases. First, during jet development to the point of air delivery (separation distance is important); here entrainment is dependent on nozzle design of the air distribution device and the initial conditions.[19–24] Second, during interaction between air jets from supply devices (or other momentum induced flows) and buoyancy flows in the room i.e. human convective boundary layer (CBL) or other thermal plumes from indoor heat sources. Here, control of entrainment is very hard and is dependent on system setup (location of the supply device, airflow direction etc.). The importance of the interaction between the CBL and the air supply jet on inhaled air quality and comfort has been addressed although more studies are needed to tackle pollution reduction and entrainment control.[2,21,25–28]

Herein, we have distinguished air distribution principles in dilution systems and delivery capacity systems based on prior knowledge from literature. We suggest that the most central findings in studies involving delivery capacity systems should be put into perspective with prior knowledge. Possible sources of error, which may have distorted the results, should also be discussed. Emphasis should be placed on the appropriate testing methods, as applying traditional methods commonly used in dilution capacity systems may not accurately rate or estimate the system performance. Discussions should also present authors' interpretation of the meaning of the results. The authors are encouraged to make recommendations based on the earlier knowledge and the present results. System designers and researchers should also consider that delivery systems will also be bound to limitations such as the distance at which the jet concentration equals the room ambient concentration. Other factors, will involve jet exit conditions were low initial velocity (low momentum) will reduce the penetration distance and increase jet oscillation,[29] and high target velocities or low supply temperatures may increase the risk of thermal discomfort.[2]

### *Research opportunities*

Currently there are no standards or stipulated guidelines for design and implementation of delivery capacity systems. Therefore, for these systems to be realized, as stated by Melikov[11] "substantial research on development, performance, implementation, operation, and maintenance of new solutions that comply with this strategy is needed." There are opportunities to explore research on:

1. Inclusion of entrainment as a performance measure in design and operation of delivery air distribution devices. Entrainment is the most important single parameter especially that the delivered air quality is dependent on it. Thus, methods of determining entrainment in delivery capacity systems need to be defined. An example of such a method could be the delivery capacity concept discussed herein and used by Kabanshi and Sandberg.[23]
2. Investigate initial conditions suitable for optimized operation of delivery capacity systems. To the authors knowledge, few studies exists that address entrainment with focus on the near field and within initial conditions suitable for air distribution in delivery capacity systems. Additionally, the influence of nozzle diameter variation is another interesting aspect not only in applications of air distribution in delivery capacity systems but is also of fundamental importance in jet theory. For interested researchers, see Malmström [30]. While a lot has been done on performance of different delivery capacity air distribution diffusers [19–22] there are still no design guidelines in place. Other researchers [21] have also expressed the need to address this. This also offers research opportunities and help develop design guidelines for air distribution diffusers that also factor in entrainment.

## Conclusions

Principles of air distribution between dilution and delivery capacity systems are distinct. Dilution capacity systems like mixing ventilation has room air and/or contaminants return (visit) to the same region several times. During which the contaminants are diluted to the concentration level admitted by the dilution capacity, controlled through the supplied ventilation flow rate, and the contaminant is ideally spread uniformly over the whole volume of the room. On the other hand, in systems intended to deliver clean air, the delivery capacity at the target distance x from the supply is governed by the ratio of room contaminants entrained into a jet flow to that of the volumetric flow rate at that target point in the air stream, $Q_e(x)/Q_x$. The only way to improve delivered air quality or extend the supply conditions to the target region is to reduce entrainment. Therefore, there is a need of a more precise definition of what is meant by delivery capacity systems such as personalized ventilation. At what distance between supply and target do we have "personalized" ventilation? Should the core region just reach the mouth of a person or should the person perhaps "inhale" a fraction of the supply ventilation conditions, which means a mixture (dilution) of ambient room air and supply air?

Development of systems for delivery of clean air calls for a need to determine and include methods to estimate the entrainment in delivery capacity systems. An example of a method proposed herein is the delivery capacity, which is defined as a fraction of the supply conditions delivered at a specific point downstream, or alternatively present the entrainment mixing factor. Other methods to diminish entrainment of ambient air is by using the properties of stable stratified flow by either supplying cold air at floor level or warm air at ceiling level.

## Authors' contribution

All authors contributed to the development of this paper.

## Conflict of interest

The Author(s) declare(s) that there is no conflict of interest

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