IS BUILDING VENTILATION A PROCESS OF DILUTING CONTAMINANTS OR DELIVERING CLEAN AIR?

Mats Sandberg[1 *], Hans Wigö[1], Alan Kabanshi[1]

[1]University of Gävle, Sweden
[*]*Corresponding email: mats.sandberg@hig.se*

SUMMARY

The purpose of the paper is to discuss the performance of air distribution systems intended for dilution of contaminants and those intended for delivery of clean air to local regions within rooms. At first the systems are distinguished by their visiting frequency behaviour. The performance of the systems with respect to their possibility to influence the concentration due to contaminants is dealt with by the concept dilution capacity for mixing systems and by introduction of the concept delivery capacity for systems intended for delivery of clean air locally. Various ways of realizing systems for supply of clean air to regions within a room are presented and their pros and cons are discussed. The most important single parameter is the entrainment of ambient air into the primary flow that drives the airflow in the room.

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

1 INTRODUCTION

Traditionally, an air distribution system serving a whole room is viewed as a system where the supplied flow rate provides a dilution capacity that lowers the concentrations of contaminants generated in the room. During the last decades systems are introduced or suggested that are marked as systems that are providing clean air to regions within a room. One type is called personalized systems (Melikov, 2004). Optimal performance of dilution capacity is obtained with a large entrainment that contrasts with the requirement of a low entrainment for optimal performance of delivering clean air. This calls for the need to introduce concepts that discriminates between the performances of the different air distribution systems. We hope that this paper will contribute to introduce a fruitful discussion.

2 BASIC CONCEPTS CHARACHTERIZING AIR DISTRIBUTION - DRIVING FLOW

2.1 Return probability, visitation frequency and two population fluid

Generally, the flow in a room has a recirculation. Therefore, contaminants and air leaving a region may come back to the same region, see Fugure1. ($\dot{m}$ is the generation rate of a contaminant). The probability to return is r (Chunga et al., 2017) and subsequently the probability to leave for never returning is (1-r). The corresponding flowrates 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.

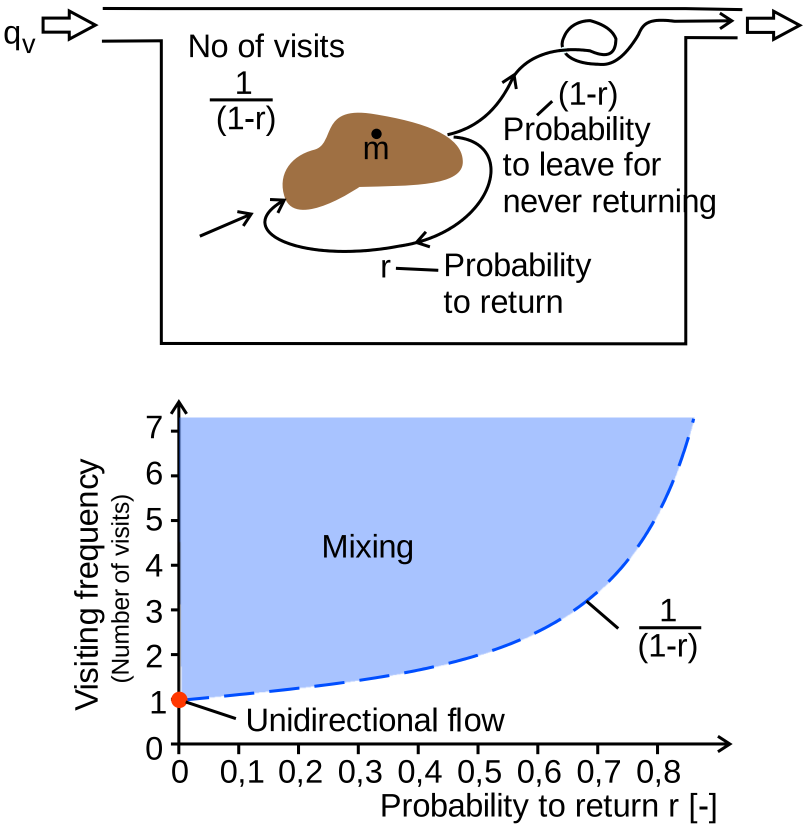

Figure 1. Top: Definition of probabilities; Bottom: Visiting frequency and probability to return

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 (Kato et al., 2003) expressed in terms of the return probability (Chunga et al., 2017) is

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

When the probability to return is zero the visitation frequency is equal to 1 and in other cases it is larger than 1 so there is more than one visit. This leads to the following natural classification of air distribution systems; Systems with the probability to return equal to zero are system with unidirectional flow and the other systems are mixing systems. Subsequently, mixing in a room in the context of ventilation means that the air and/or the contaminant returns to the actual region.

2.2 Driving flow and mixing factor due to entrainment

The driving flow is the 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 a plume, or the boundary flow generated by buoyancy sources. An example of this is displacement ventilation. The flow elements controlling the air flow in a room are in contact with the surrounding air by entrainment of ambient air.

The flow rate $q_{Entrained}(x)$ entrained into the driving flow along the distance between the supply point to the location x from the supply is

$$q_{Entrained}(x) = (q(x) - q_{Supply}) \quad (2)$$

The mixing factor due to entrainment at location x is defined as the amount of ambient air entrained at the position x divided by the flow rate,q(x), at position x.

$$Mix_{Entrain}(x) = q_{Entrain}(x)/q(x) = (1-q_{Supply}/q(x)) \quad (3)$$

This mixing factor gives the fraction of the flow consisting of ambient room air. With increasing distance, the fraction of entrained air increases and the theoretical limit of the mixing factor is 1, see Fugure2. In case the driving flow is starting from zero, air in the flow consists from the very beginning of entrained air, see Figure 5, then $q_{Entrain}(x)$ =q(x) and $Mix_{Entrain}(x)$ =q(x)/q(x) = 1. The range of the mixing factor is $0 \leq Mix_{Entrain}(x) \leq 1$. $Mix_{Entrain}(x) = 0$ is the ideal condition for delivery systems.

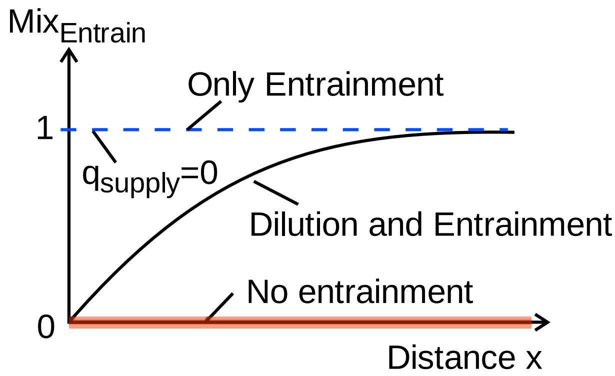

Figure 2. The mixing factor due to entrainment as a function of distance from the supply

3 AIR DISTRIBUTION SYSTEMS

3.1 Mixing systems and their dilution capacity

Figure 3 shows a typical air distribution system for mixing ventilation. By entrainment, an internal flow rate larger than ventilation flow rate is setup. Therefore, the air within the room has to queue before it can leave the room through the extract air terminal. The queueing is manifested in such a way that the air is going round several times within the room before it leaves the room. The air visits the indicated region four times before it leaves the room. According to Equation 1 the probability to return is r = 0.75.

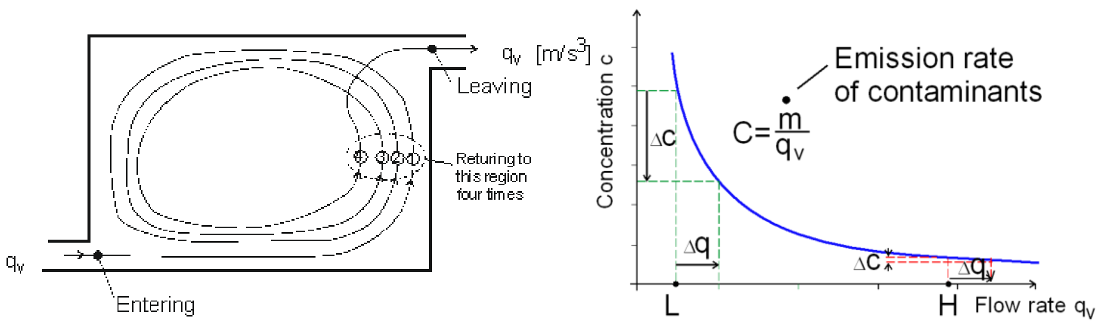

Figure 3. Left: Archetype of a mixing system; Right: Dilution curve (L: Low flowrate H: High flowrate)

The dilution curve highlights the fact that ventilation at conditions indicated by L is very important. A small increase in the ventilation flow rate (Δq) 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.

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

Fugure4 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 areathrough 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 give rise to an adverse pressure gradient, a well-known “trouble maker” in fluid mechanics. 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}, the velocity decreases. This decrease is compensated by an increase in pressure Δp (ρ is the density of air);

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

This causes an unstable air distribution in the room which may result in that supply air being focused to smaller regions (break through), a well-known phenomenon from supply from perforated ceilings, Rydberg (1963). The remedy for this is shown in case c, where entrainment is made possible by supplying over an area less than the floor area (Huesmann, 1966). 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 flowrate in the driving flow rate (q_p) is equal to the supply flow rate (q_v) of ventilation air (Etheridge & Sandberg, 1996 p. 425). 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 ventilation.

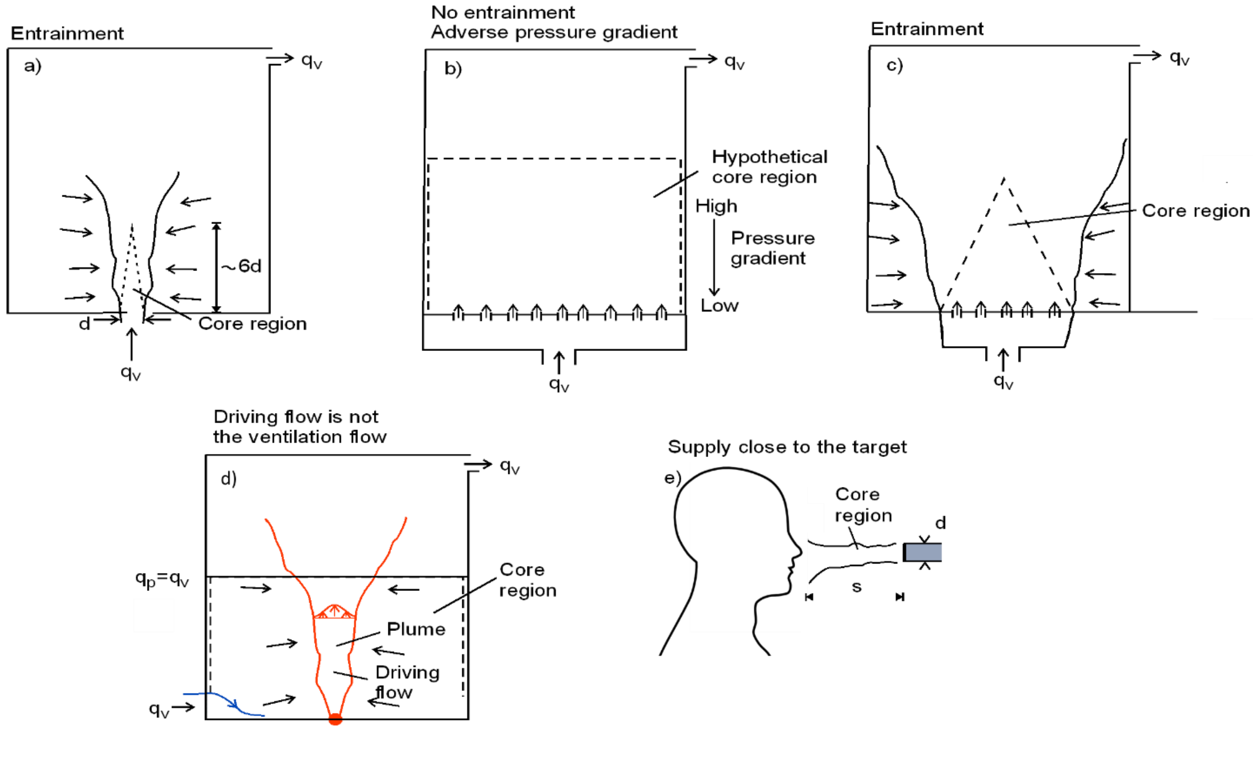

Figure 4. Direct supply of clean air. a-d) expanding the core region, e) Supply close to target

These systems 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, see Figure 5.

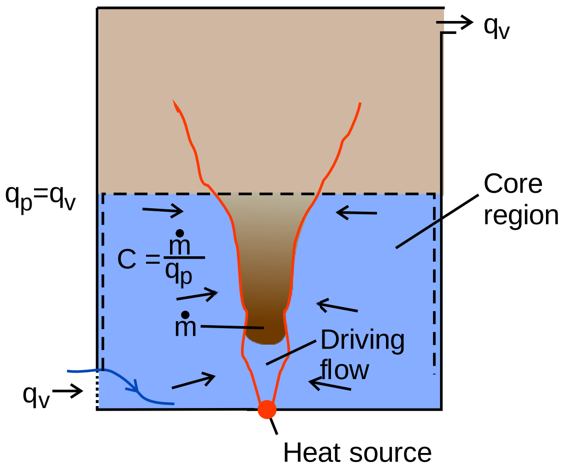

Figure 5. Due to entrainment of ambient ventilation air the dilution capacity is equal to the flow rate q_p in the plume

3.3 Delivery capacity of clean air

One way of defining the delivery capacity is to state the distance to the end of the core region, refer to Figure 4. A natural question to ask is; how clean is the air when it arrives at the target? This question can be answered by introducing a test case with polluted air and explore the resulting concentration. Such a test case is shown in Figure 6. Clean air is supplied into a room with a uniform ambient concentration, C_{Amb}.

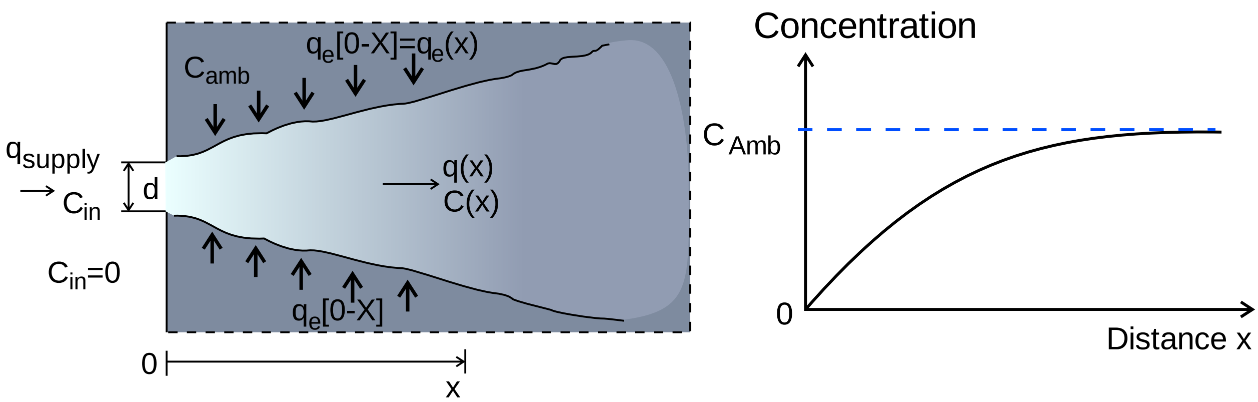

Figure 6. Supply of clean air, C_{in} = 0, into a room filled with a pollutant of uniform concentration

At distance x we have the mass flow balance

$$q_{Entrain}(x)C_{Amb} = (q(x) - q_{Supply})C_{Amb} = q(x)C(x) \tag{5}$$

Which gives the concentration in the air stream

$$C(x) = C_{Amb} * Mix_{Entrain}(x) = C_{Amb}\frac{q_{Entrain(x)}}{q(x)} \tag{6}$$

The concentration in the air stream is controlled by $q_{Entrain}(x)/q(x)$) in contrast to mixing system where the concentration is controlled by the supply flow rate q_{Supply}. Therefore, in delivery capacity systems the only way to improve the situation is to reduce the entrainment. The delivery capacity can be defined as the distance to where the concentration in the air stream is a certain fraction of the ambient concentration, say 50 % or 90%.

4 DISCUSSION

The most central findings in studies involving delivery capacity should be put into perspective with the 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 becomes close the room ambient concentration. Other factors, will involve jet exit conditions were low Reynold numbers (low flow force) will reduce the penetration distance and increase jet oscillation (Kabanshi et al, 2017), and high target velocities or low temperatures may increase the risk of thermal discomfort (Melikov, 2004).

5 CONCLUSIONS

Mixing systems are systems where air and contaminants return (visit) the same region several times. After that the contaminant has been diluted to the concentration level admitted by the dilution capacity, controlled by the supplied ventilation flow rate, the contaminant is spread over the whole volume of the room. In systems intended to deliver clean the delivery capacity at distance x from the supply is governed by the ratio between the flow rate of entrained air $q_{Entrain}(x)$ and the flow rate q(x) in the air stream, $q_{Entrain}(x)/q_{(x)}$supply. The deliver capacity can be defined as the distance to the end of the core region (maximum delivery capacity) or the distance to where the concentration is a given fraction of the ambient concentration, let's say 50 % or 90 %. Development of systems for delivery of clean air calls for a need of methods for measuring the entrainment. An example of a method is reported in Kabanshi et al (2018). Entrainment of ambient air can be diminished by using the properties of stable stratified flow by either supplying cold air at floor level or warm air at ceiling level.

There is a need of a more precisely definition of what is meant by 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 "swallow" a fraction of the core region?

REFERENCES

Chunga J, Limb E, Sandberg M, Ito K (2017) Returning and net escape probabilities of contaminant at a local point in indoor environment; Building and Environment, Vol. 125, 67-76

Etheridge M, Sandberg M (1996) Building Ventilation Theory and Measurement John Wiley

Huesmann,K (1966) Eigenschaften turbulenter Strahlenbundel Chemie-Ing- - Techn. 38/Heft 3

Kabanshi A, Sandberg M, Wigö H (2018) Measurement of Entrainment into an Axisymmetric Jet using Temperature as a Tracer: A Pilot Study. Proceedings Roomvent 2018 Helsinki

Kabanshi, A, Sattari, A, Linden, E, Wigö, H, & Sandberg, M (2017). Experimental study on contaminant entrainment in air distribution systems with free jets. In Healthy Buildings 2017 Europe, July 2-5, 2017, Lublin, Poland.

Kato S, Ito K, Murakami S (2003). Indoor Air 13 (2), 182-193, 2003. 45

Melikov, AK (2004). Personalized ventilation. Indoor Air, 14(s7), 157-167

Rydberg, J(1963)Lufteinblasung durch perforierte Decken, Gesundsheits-Ingenieur 84 H. 2, S .33-38