International Journal of Aviation, Aeronautics, and Aerospace

Volume 9 | Issue 2 Article 2

2022

Modelling Air Quality in an Aircraft Passenger Cabin using Health Care Standards

Bert Silich
Vector Vantage LLC, bsilich@vectorvantage.com

A method to maintain safe air quality standards in an aircraft passenger cabin will be presented. Safe air quality with respect to aerosols in a closed space is important to protect people in their environment. The COVID-19 pandemic has increased the significance of this topic. This article is based on equations from Silich (2021) and presents these prior equations in a different format that can help to provide greater insight to the behavior of aerosols in a well-mixed space. One purpose of this article is to enhance our understanding of how an aerosol behaves in a closed space where dilution ventilation is the method used to clear the aerosol. The primary focus will be that of an aircraft passenger cabin. The model used is best applied to an aviation scenario by understanding its relationship to health care ventilation requirements.

Flow rate, Q, and air changes per hour, ACH, are common terms used in ventilation engineering. These two terms are related where $\mathrm{Q} = \mathrm{ACH} * \mathrm{Volume}$. Each of these terms contribute important but different characteristics to the solution of an aerosol in a closed space. It will be shown that the steady state solution for an aerosol concentration depends on the flow rates and the time to decay to the steady state solution depends on the ACH. This result is independent of the volume, V_{ref}, of the space. The role of recycled HEPA filtration will also be discussed.

Model Analysis

Figure 1, along with Table 1, represents a free-body diagram model of a closed space with HEPA filtration using dilution ventilation. For an aircraft passenger cabin the two main sources of flow rate are from the engine bleed air system represented by $\mathrm{Q_{in}}$, and from recycled HEPA filtration represented by $\mathrm{Q_{HEPA}}$. In modern aircraft $\mathrm{Q_{HEPA}}$ can be as much as 50% of the total flow rate, $(\mathrm{Q_{in}} + \mathrm{Q_{HEPA}})$.

Table 1
Definitions

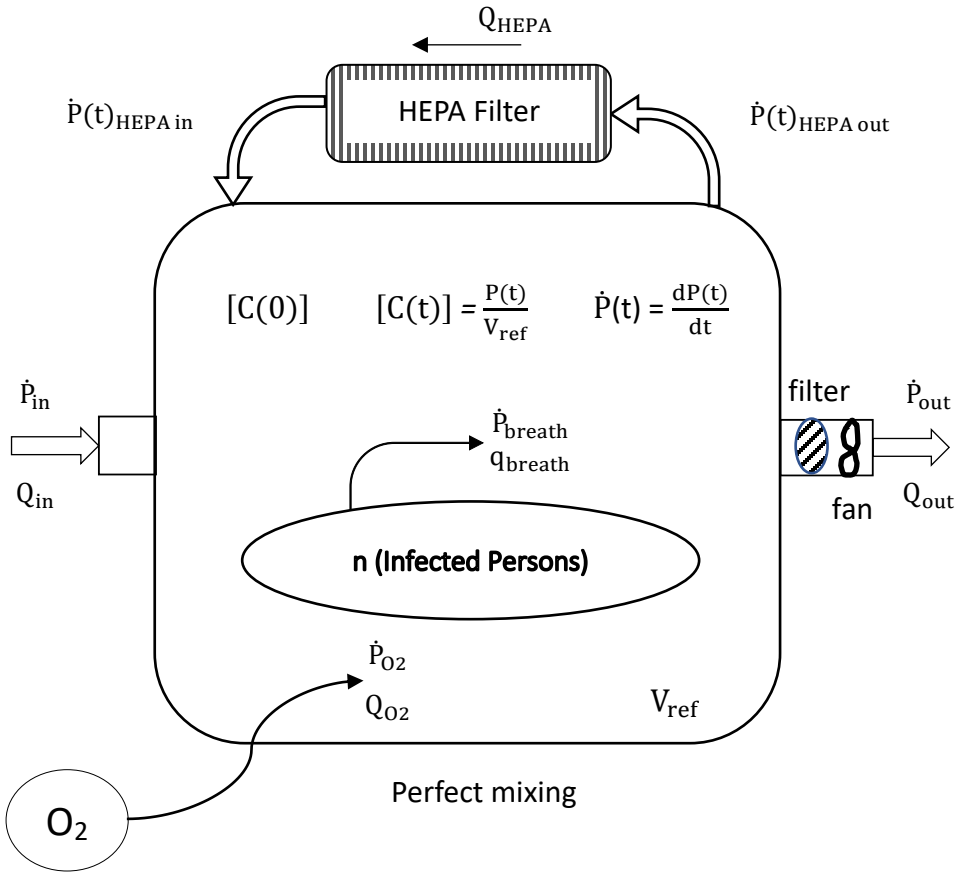
$$\dot{\mathrm{P}}_{\mathrm{in}} = \mathrm{Q_{in}}[\mathrm{C_{in}}] \qquad \dot{\mathrm{P}}(\mathrm{t})_{\mathrm{HEPA\ out}} = \mathrm{Q_{HEPA}}[\mathrm{C(t)}]$$

$$\dot{\mathrm{P}}_{\mathrm{out}} = \mathrm{Q_{out}}[\mathrm{C(t)}] \qquad \dot{\mathrm{P}}(\mathrm{t})_{\mathrm{HEPA\ in}} = (1 - \mathrm{HEPA})\mathrm{Q_{HEPA}}[\mathrm{C(t)}]$$

$$\dot{\mathrm{P}}_{\mathrm{breath}} = \mathrm{n} * \mathrm{q_{breath}} * [\mathrm{C_{breath}}] \qquad \mathrm{HEPA} = \frac{\mathrm{HEPA\%}}{100}$$

$$\dot{\mathrm{P}}_{\mathrm{O2}} = \mathrm{Q_{O2}}[\mathrm{C_{O2}}] \qquad \mathrm{Q_i} = \mathrm{ACH_i} * \mathrm{V_{ref}}$$

Figure 1
Well-Mixed Aerosol Model of a Closed Space



Equation (1) shows the aerosol concentration ratio, ACR(t), of a well-mixed aerosol in a closed space. Previous publications use the term CCR(t), contaminant concentration ratio, this article will use the term ACR(t) to emphasize these solutions only apply to aerosols. Dilution ventilation requires the environment to be well-mixed. See the appendix for details. The main source of contamination is from infected passengers. While we can account for contamination from the engine bleed air and the passenger oxygen masks, this is unlikely and will be considered equal to zero in this discussion.

$$\frac{[C(t)]}{[C_{breath}]} = ACR(t) = \left(\frac{n * q_{breath}}{Q_{out} + HEPA * Q_{HEPA}}\right) + \left(\frac{[C(0)]}{[C_{breath}]} - \frac{n * q_{breath}}{Q_{out} + HEPA * Q_{HEPA}}\right) * e^{-(ACH_{out} + HEPA * ACH_{HEPA}) * t} \quad (1)$$

Various decay times can be determined from the exponential function. See the appendix for details. The time for 99% of the decay, $T_{99\%}$, towards the steady state solution depends on the total ACH of the closed space.

$$T_{99\%} = \frac{4.6}{(ACH_{out} + HEPA * ACH_{HEPA})} = 2 * T_{90\%} \quad (2)$$

It is interesting to note that these two solutions do not depend on the volume of the space, V_{ref}. Any two spaces, regardless of their relative volumes, with identical contamination sources, total flow rates and total ACHs will have identical $ACR(t)$ and $T_{99\%}$ results.

The exponential term in the first equation will decay towards zero leaving $n * q_{breath}/(Q_{out} + HEPA * Q_{HEPA})$ as the remaining constant steady state aerosol concentration ratio term, $ACR(\infty)$. Equation (1) shows the *steady state solution depends on the total flow rates* of the system. Equation (2) shows the *time to decay to the steady state solution depends on the total air changes per hour* of the system. This is how these two related terms contribute to the solution in different ways.

It is worth noting that the steady state solution makes no difference if the flow rate is achieved by the out flow or the HEPA filter. All that matters is the total flow rate. Also, the decay of this equation does not depend on whether the ACH is due to the out flow or due to the HEPA filter. Similarly, all that matters is the total ACH.

The formula for the number of particles inhaled by one person breathing at a constant rate, q_{inh}, was also calculated in the appendix. In practical applications, measuring $[C_{breath}]$ can be challenging; calculating the particles inhaled is more for scientific applications. It is worth noting this formula shows the number of inhaled particles is related to the area under the $ACR(t)$ curve in Figure 2.

The aerosol concentration ratio does not guarantee an absolute level of aerosol concentration. Instead, with dilution ventilation there is a percent reduction in the aerosol level with respect to the source aerosol level, $[C_{breath}]$, which typically is not known. This limitation does not prohibit us from using the $ACR(t)$ to ensure a reasonable and consistent level of air quality safety. Reviewing health care applications can help to understand this.

Background

The general model in figure 1 is not only applicable to an aircraft passenger cabin but it can also be used in many scenarios including a hospital isolation room. A standard U.S. hospital isolation room holding one patient has a volume of approximately 30 m^3 and is required to function at 12 ACH, CDC (2007). A healthy individual breaths about 0.5 liters/breath at a rate of 12 up to 20 breaths/minute. This equates to a $q_{breath} = 0.6\ m^3/hour$. A sick individual with respiratory disease might require a respiratory rate twice that of normal but typically they cannot sustain this rate for a significant length of time without medical assistance. So, using a twice the normal value of $q_{breath} = 1.2\ m^3/hour$ is a reasonable worst-case value, Bazant et al. In addition, assuming the aerosol is exhaled at a constant rate as opposed to intermittently as with coughing is another worst-case assumption. Using equation (1), a standard isolation room, with a single patient, will function at a total flow rate of 360 m^3/hour and achieve a steady state $ACR(\infty) = 0.33\%$. In other words, an isolation room provides an aerosol concentration level of 0.33% of the source concentration, $[C_{breath}]$. Again, this source concentration is not known in

clinical scenarios. Using equation (2), we see for an isolation room with a total of 12 ACH, the decay time for $T_{99\%}$ is 23 minutes. Further details can be found in Silich (2020).

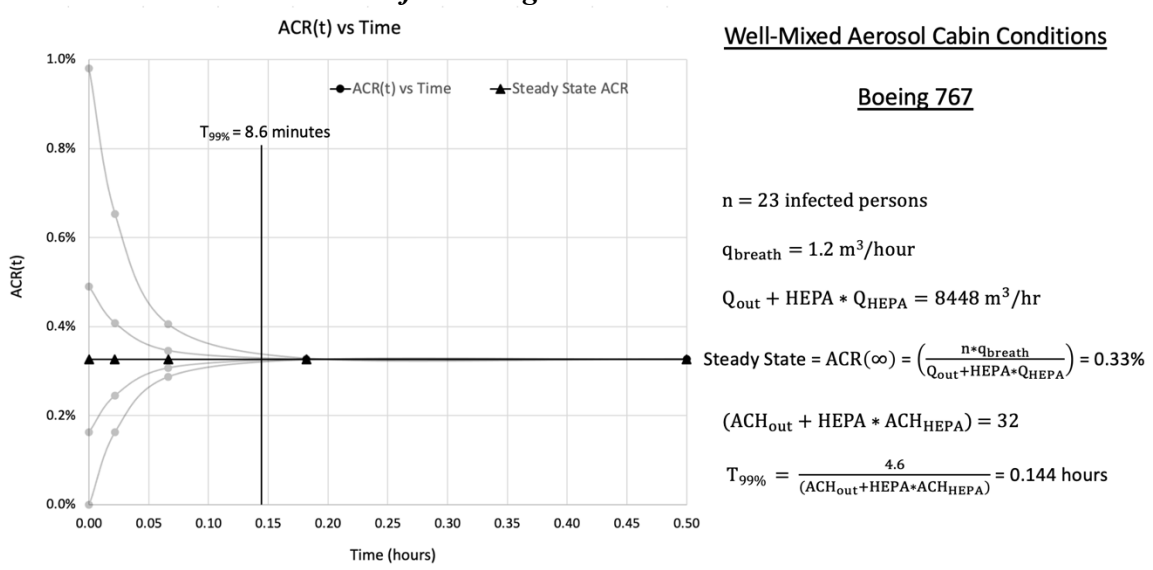
When dealing with aerosol health issues an isolation room might be considered the current gold standard and is a good reference frame to keep in mind. An aerosol concentration ratio of 0.33% does not guarantee safety from every possible pathogen. Each pathogen needs to be studied to determine if an $ACR(\infty) = 0.33\%$ is a safe level for a specific exposure time. Realize, health care providers still wear some level of mask protection when entering these isolation rooms for additional protection.

Boeing 767

Figure 2 shows the ACR(t) graph for a Boeing 767. In this example, we estimate there are 23 infected passengers on board based on a fictitious disease's prevalence in the general population. See the appendix in Silich (2021) for details of this calculation. They all have a worst-case $q_{breath} = 1.2$ m^3/hour. The combined ACH from out flow and HEPA filtration for this aircraft is 32. At a volume of 264 m^3 the combined out flow and HEPA flow rate is 8448 m^3/hour. Regardless of the initial aerosol concentration, these flow rates will achieve a steady state ACR(∞) value of 0.33%. The time for 99% of the decay, $T_{99\%}$, towards this steady state ACR(∞) to occur is 8.6 minutes.

Figure 2

Aerosol Concentration Ratio of a Boeing 767



It turns out the air quality for these given conditions in a Boeing 767 match the air quality of a standard U.S. isolation room. While it may be reasonable to require hospital isolation room standards as a starting point, this is not to advocate that this should be the aviation standard because a standard isolation room does not guarantee safety from all aerosol pathogens. In addition, if the time of exposure in an aircraft is longer then in an isolation room a lower ACR(∞) would be required. These conditions were used to demonstrate a method to establish acceptable standards by referring to a hospital isolation room. Realize, to achieve steady state isolation room conditions all that is required is to provide a total flow rate of 360 m^3/hour for each sickened individual. In this aircraft 23

infected persons*360 m^3/hour per infected person = 8280 m^3/hour which approximates the 8448 m^3/hour initial condition. This difference is due to the round-off error of the reference numbers. These results are also dependent on the environment being well-mixed. If this is not the case, applying this method would require multiplying results by appropriate safety factors to compensate for this shortfall. Refer to CDC (2021) for details.

Notice that if the HEPA filtration system were to be inoperative, the steady state solution for $\mathrm{ACR}(\infty)$ would increase. Also, the time to decay to the steady state solution would decrease. Increasing the engine bleed air by an amount equal to that lost from the inoperative HEPA filter, $(\mathrm{HEPA} * \mathrm{Q_{HEPA}})$, would return the steady state $\mathrm{ACR}(\infty)$ and the $T_{99\%}$ decay rate to their original values. This increase in engine bleed air requirements would decrease the engine efficiency.

Summary

The two equations presented provide insight to how an aerosol behaves in a well-mixed closed space. While an aircraft passenger cabin was highlighted, the equations can be applied to any closed space meeting the requirements of the free-body diagram in figure 1. We should realize that dilution ventilation provides a percent reduction in contamination concentration with respect to the concentration of the source, $[\mathrm{C_{breath}}]$. We should also realize for a given contaminant source flow rate, $\mathrm{q_{breath}}$, the steady state $\mathrm{ACR}(\infty)$ depends on the total flow rates of the space, $(\mathrm{Q_{out}} + \mathrm{HEPA} * \mathrm{Q_{HEPA}})$. The time to decay to this steady state value depends on the total ACH of the space, $(\mathrm{ACH_{out}} + \mathrm{HEPA} * \mathrm{ACH_{HEPA}})$.

Assuming a worst-case $\mathrm{q_{breath}} = 1.2\ m^3/\mathrm{hour}$, a closed space of any volume with a total flow rate of 360 m^3/hour per sickened individual will achieve a steady state $\mathrm{ACR}(\infty) = 0.33\%$. At 32 ACH, the time for 99% of the decay, $T_{99\%}$, towards this steady state value is 8.6 minutes.

Conclusion

The basic concept to remember is the *steady state aerosol concentration depends on the total flow rates* of the system and the *time to decay to this steady state solution depends on the total air changes per hour* of the system. Many variables cannot be controlled such as the number of infected individuals, n, in the cabin, the aerosol contaminant concentration of their breath and the inhalation flow rates of each occupant. Even with these obstacles, reasonably safe levels of air quality can be achieved using the aerosol concentration ratio, $\mathrm{ACR(t)}$, and concepts applied in hospital isolation rooms.

References

Bazant, M., & Bush, J. (2021). *A guideline to limit indoor airborne transmission of COVID-19*. https://doi.org/10.1073/pnas.2018995118

Centers for Disease Control and Prevention (2007). *Guideline for isolation precautions: Preventing transmission of infectious agents in healthcare settings - airborne infection isolation room (AIIR).* https://www.cdc.gov/infectioncontrol/guidelines/isolation/glossary.html

Centers for Disease Control and Prevention (2021). *Ventilation in buildings, updated June 2, 2021*. https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html#Ventilation-FAQs

Silich, B. A. (2020). Method to reduce aerosolized contaminant concentration exposure to healthcare workers during the COVID-19 pandemic when temporary isolation systems are required. *Western Journal of Emergency Medicine: Integrating Emergency Care with Population Health, 21*(6), 93-98. http://dx.doi.org/10.5811/westjem.2020.9.48170 Retrieved from https://escholarship.org/uc/item/8d1684jn.

Silich, B. A. (2021). A model for inhalation of infectious aerosol contaminants in an aircraft passenger cabin. *International Journal of Aviation, Aeronautics, and Aerospace, 8*(1). https://doi.org/10.15394/ijaaa.2021.1545

Appendix

Definitions

ACH	-	Air Changes / hour
ACR	-	Aerosol Concentration Ratio (ACR = CCR)
[C]	-	Concentration (particles/m^3)
CCR	-	Contaminant Concentration Ratio (CCR=ACR)
O2	-	Oxygen supply
n	-	number of identical contaminant sources
P	-	# Contaminant particles
Q , q	-	Volume flow rate (m^3/hour)
RR	-	Respiratory rate (1/hour)
t	-	time (hours)
TV	-	Tidal volume (m^3)
V_{ref}	-	Reference volume (m^3)
Virion	-	a complete virus particle

Important Relationships

[C]	=	$\frac{P}{V}$
$[C_{out}]$	=	$[C_{V\,ref}]$
q	=	$(TV * RR)$
Q	=	$ACH * V_{ref}$
$\dot{P} = \frac{dP}{dt}$	=	$Q * [C]$
1 particle	=	1 virion

Conservation of particle flow is applied to figure 1 with terms in Table 1. Using a dilution ventilation approach requires perfect mixing of the aerosolized particles of which all sizes are equally affected by the air flow. Typically, aerosol particles are less than or equal to 5 microns and can take hours to days to settle to the ground per CDC (2021).

$$\dot{P}(t) = \sum \dot{P}(t)_{in} - \sum \dot{P}(t)_{out} \quad \text{(particles/hour)}$$

$$\dot{P}(t) = \left(\dot{P}_{breath} + \dot{P}_{in} + \dot{P}(t)_{HEPA\,in} + \dot{P}_{O2}\right) - \left(\dot{P}_{out} + \dot{P}(t)_{HEPA\,out}\right)$$

$$\dot{P}(t) = \left(\dot{P}_{breath} + \dot{P}_{in} + (1 - HEPA)Q_{HEPA}[C(t)] + \dot{P}_{O2}\right) - (Q_{out} + Q_{HEPA})[C(t)]$$

$$\dot{P}(t) + \frac{(Q_{out} + HEPA * Q_{HEPA})}{V_{ref}} * P(t) = (\dot{P}_{breath} + \dot{P}_{in} + \dot{P}_{O2})$$

This differential equation for dilution ventilation with aerosol particles in a well-mixed space can be written in terms of ACH.

$$\dot{P}(t) + (ACH_{out} + HEPA * ACH_{HEPA}) * P(t) = (\dot{P}_{breath} + \dot{P}_{O2} + \dot{P}_{in})$$

The solution to this differential equation can be written in this form. All the terms are constant except for t.

$$P(t) = \left(\frac{\dot{P}_{breath}+\dot{P}_{in}+\dot{P}_{O2}}{ACH_{out}+HEPA*ACH_{HEPA}}\right) + \left(P(0) - \frac{\dot{P}_{breath}+\dot{P}_{in}+\dot{P}_{O2}}{ACH_{out}+HEPA*ACH_{HEPA}}\right) * e^{-(ACH_{out}+HEPA*ACH_{HEPA})* t}$$

Next, divide by V_{ref} and substitute for $\dot{P}_{breath}$.

$$[C(t)] = \left(\frac{n*q_{breath}*[C_{breath}]+\dot{P}_{in}+\dot{P}_{O2}}{Q_{out}+HEPA*Q_{HEPA}}\right) + \left([C(0)] - \frac{n*q_{breath}*[C_{breath}]+\dot{P}_{in}+\dot{P}_{O2}}{Q_{out}+HEPA*Q_{HEPA}}\right) * e^{-(ACH_{out}+HEPA*ACH_{HEPA})* t}$$

Assume $\dot{P}_{O2}$ and $\dot{P}_{in}$ are not sources of contamination and therefore equal zero. Now divide by the constant $[C_{breath}]$ to obtain the contaminant concentration ratio, ACR(t).

$$\frac{[C(t)]}{[C_{breath}]} = ACR(t) = \left(\frac{n*q_{breath}}{Q_{out}+HEPA*Q_{HEPA}}\right) + \left(\frac{[C(0)]}{[C_{breath}]} - \frac{n*q_{breath}}{Q_{out}+HEPA*Q_{HEPA}}\right) * e^{-(ACH_{out}+HEPA*ACH_{HEPA})* t}$$

This first expression on the right-hand side is the steady state term. The second expression on the right-hand side decays towards zero. Various decay times, $T_{xy\%}$, can be determined from the exponential function.

$$(1 - 0.xy) = e^{-(ACH_{out}+HEPA*ACH_{HEPA})*T_{xy\%}}$$

$$T_{xy\%} = \frac{\ln(1 - 0.xy)}{-(ACH_{out}+HEPA*ACH_{HEPA})}$$

$$T_{99\%} = \frac{4.6}{(ACH_{out}+HEPA*ACH_{HEPA})} = 2 * T_{90\%}$$

To find the particles inhaled by one person breathing at a constant rate, q_{inh}, we let n=1. $\dot{P}_{O2}$ and $\dot{P}_{in}$ remain equal to zero. Since [C(t)] varies with time, integration is required. Realize, the number of inhaled particles is related to the area under the ACR(t) curve in figure 2.

$$P_{inh} = q_{inh}\int_{t1}^{t2}[C(t)] * dt = q_{inh}[C_{breath}]\int_{t1}^{t2} ACR(t) * dt$$

$$\frac{P_{inh}}{q_{inh}[C_{breath}]} = \int_{t1}^{t2}\left(\left(\frac{q_{breath}}{Q_{out} + HEPA * Q_{HEPA}}\right) + \left(\frac{[C(0)]}{[C_{breath}]} - \frac{q_{breath}}{Q_{out} + HEPA * Q_{HEPA}}\right) * e^{-(ACH_{out}+HEPA*ACH_{HEPA})* t}\right) * dt$$

$$\frac{P_{inh}}{q_{inh}[C_{breath}]} = \left[\left(\frac{q_{breath}}{Q_{out} + HEPA * Q_{HEPA}}\right) * t - \left(\frac{\frac{[C(0)]}{[C_{breath}]} - \frac{q_{breath}}{Q_{out} + HEPA * Q_{HEPA}}}{ACH_{out} + HEPA * ACH_{HEPA}}\right) * e^{-(ACH_{out}+HEPA*ACH_{HEPA})* t}\right]\Bigg|_{t1}^{t2}$$