

Germes and Flying: Developing Ventilation System Criteria

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ABSTRACT

The development of ventilation and filter design criteria to limit exposures to airborne infectious aerosols requires knowledge of infectious aerosol generation and inhalation rates, ventilation and filtration/kill rates, ventilation efficiency, occupancy spatial volumes and exposure times. This study calculates respirable infectious aerosol exposure and normal at rest inhalation quantities by a group of persons using in-practice values for these spatial and HVAC parameters and an assumed influenza aerosol generation rate from the normally exhaled breath of one ill person for eight settings including both narrow and wide-body aircraft.

INTRODUCTION

Interest in determining the role that HVAC systems/ECS play in the transmission of infectious disease in passenger aircraft is growing with a special conference held on the subject in 2009.¹ Now in 2011 the American Society of Heating, Refrigerating and Air- Conditioning Engineers has issued a Request for Proposals to begin the first of a planned series of investigations on this subject in various building and transportation vehicle environments.²

Research in this area includes the measurement of influenza virus in the normally exhaled breath of ill persons;³ the association of influenza transmission with low humidity environments and of common cold transmission with high humidity situations;^{4 5} the measurement of human generated airborne virus and bacteria in aircraft air;⁶ the movement of airborne particles due to turbulence at HVAC diffuser flow boundary layers and people movement;^{7 8 9 10 11} the role of filters;^{12 13} the control of stack pressures to improve cabin

humidity;¹⁴ and the calculated impacts of occupancy density and exposure duration, as well as ventilation and filtration/kill rate, on occupant human bioeffluent exposure.^{15 16}

This current study extends the latter research.

GOVERNING EQUATIONS

The time dependence of airborne infectious disease occupant-generated infectious aerosol concentration in a uniformly mixed system, like any occupant bioeffluent concentration (e.g. human breath carbon dioxide, and perspiration, perfume, clothing and skin oil volatile organic compound emissions), is governed by occupancy density (OD), air supply rate per person, the HVAC system effectiveness in getting that supply air to the breathing zone, and the quality of the supply air, as

$$C = [N/(V \cdot V_e)] [1 - \exp(-V \cdot V_e \cdot t/v)] \quad (1)$$

Where

- C = bioeffluent infectious aerosol concentration in the space at time t, virus/L
- N = rate of bioeffluent infectious aerosol generation/person in the space, virus/s/p
- t = duration of infectious aerosol generation, s
- v = spatial volume/person, L/p
- V = infectious aerosol-free ventilation rate (HVAC outside air + filtered recirculation air + envelope infiltration air) per person, L/s/p
- V_e = efficiency of supplying the ventilation air to each occupant's breathing zone.
- V_e = 1 in a uniformly mixed system.

Infectious aerosol dose, D , is the time-integrated function of individual inhalation rate I , and aerosol concentration C , is given by

$$D = \int I C dt \quad (2)$$

Where

D = virus inhaled or dose, virus

I = inhalation rate, L/s

INPUT DATA

Infectious aerosol free ventilation rate per person is a combination of HVAC supplied outdoor air, filtered recirculation air and infiltration air.

Minimum outside air supply rates for building environments are generally provided by ASHRAE 62.¹⁷ Transportation environment outside air supply rates are provided by ASHRAE Standard 161 in the case of aircraft¹⁸, while values are chosen based on general convention in other cases. Normally in practice rates are somewhat higher and where these are known, practice values have been used.

The volume of infectious aerosol-free filtered air is calculated by multiplying the recirculation rate by the filter/kill device effectiveness in removing 0.3 micron and larger particles, assuming that infectious aerosols are in this size range.¹² For the two aircraft types, single and two aisles, ASHRAE Standard 161 calls for a minimum of 7.5 cfm/p passing through a HEPA filter in an aircraft recirculation system. For this analysis, all aircraft will be assumed to have a HEPA filter and it will be assumed to remove 100% of human generated infectious aerosols in a single pass.

In other settings, less efficient filtration/kill might be involved. New office HVAC systems typically use MERV 13 filters, for example.¹⁹ These filters remove 30% of 0.3 micron particles and some 75% of particles between 0.3 and 1 micron diameter at typical filter face velocities.²⁰ Since minimum filtered air recirculation rates for offices typically are some 80 cfm/p based upon meeting thermal demand, this recirculation rate through a Merv 13 filter equates to 60 cfm/p passing through a HEPA filter in terms of number of 0.3 to 1 micron particles that can be diluted. Assuming this particle range removal efficiency equates to infectious particle removal, then for an office environment with 97 cfm/p of total air supply, $V=77$ cfm/p of infectious aerosol-free air comprised of 17 cfm/p of outside air and 60 cfm/p of 0.3 micron and larger free filtered air. To this is added any envelope infiltration air, which like HVAC supplied outside air, is assumed free of occupant generated infectious disease aerosols. To be conservative in this study, office filters are assumed to remove 30% of human generated infectious

aerosols in a single pass of the 80 cfm/p recirculation air flow.

For the other environments, the filtered recirculation rate used is the same as the outside air rate specified by ASHRAE. The single pass filter efficiencies in removing human generated infectious aerosols used in this analysis are 15% for a theater, and 0% for a stadium, a classroom and a subway car.

A 0.3 ACH envelope infiltration rate is used for all environments with the exception of aircraft where there is no infiltration during flight, and subway cars where infiltration rate is relatively high due to frequent stops with open doors and a 54 ACH rate is used.

V_e tends to be lower the higher the occupancy density. Thus the lowest V_e 's used are for a fully loaded subway car and a narrow-body aircraft ($V_e = 0.65$). The next lowest V_e is for a stadium ($V_e = 0.9$). The remaining settings are assigned a V_e of 1.

Spatial volumes per person used are based on occupant densities per unit floor area and assumed ceiling heights.

The design exposure times are the longest times that a person typically might be exposed to another infected person in each setting. The times chosen range from 15 minutes in a subway car to 4 hours in a stadium spectator area or theater, to 6 hours in a classroom or narrow-body jet, to 8 hours in an office to 14 hours in an intercontinental flight.

Regarding virus generation rate, Fabian *et al* found between < 3.2 to 20 influenza virus RNA copies per minute (up to 1,200 virus per hour) in the exhaled normal at-rest breath (tidal breathing) of infected persons. Seventy percent of the 67 to 8,500 particles/liter measured in the breath of these persons had diameters between 0.3 and 0.5 microns, with rarely any larger than 5 microns. Based on these findings, an influenza virus generation rate of 11 per minute is used.

Normal 'at rest' inhalation rates of 0.15 L/s/p are used for the group of exposed individuals surrounding the infected person.²¹

All input data are provided in [Table 1](#).

FINDINGS

The calculated airborne virus concentrations versus time are illustrated in [Figure 1](#). Calculated airborne virus concentrations in the air of a group of 20 persons generated by one ill person over the first 60 minutes of exposure illustrate the role of the ratio of ventilation rate, V/V_e divided by spatial volume per person, v . The smaller the

Table 1. Input Data

Location	Subway car	Aircraft, narrow-body	Aircraft, wide-body	Classroom 9+	Auditorium, theater	Classroom 3-8	Stadium spectator area	Office
Spatial vol./p, v (m ³)	0.7	1.0	1.6	8.1	10.2	11.3	26.6	28.3
Group design exposure time (h)	0.5	6.0	14.0	6.0	4.0	6.0	4.0	8.0
Ve	0.65	0.65	1.00	1.00	1.00	1.00	0.90	1.00
Infection-free ventilation air, all sources, V*Ve (L/p)	8.9	6.1	11.8	10.9	10.6	12.1	11.3	23.1
V*Ve/v	13.1	6.1	7.4	1.3	1.0	1.1	0.4	0.8
Outside air changes, all sources (ACH)	72.7	15.3	12.8	3.0	1.2	2.5	1.7	1.5
Infection-free HVAC outside air (L/s/p)	3.5	4.2	5.7	6.1	2.7	7.1	10.4	9.4
HVAC Recirc air (L/s/p)	0.0	5.2	6.1	13.7	23.6	13.7	0.0	37.8
Filter removal of viable pathogens (%) *	0	100	100	30	30	30	0	30
Infection-free HVAC recirc air (L/s/p)	0.0	5.2	6.1	4.1	7.1	4.1	0.0	11.3
Infiltration (ACH)	54.0	0.0	0.0	0.3	0.3	0.3	0.3	0.3
Infection-free Infiltration air (L/s/p)	10.2	0.0	0.0	0.7	0.9	0.9	2.2	2.4
HVAC conditioning air (L/s/m ²)	12.7	0.15	0.18	0.06	0.20	0.05	0.34	0.04
Occupancy (Persons/1000 m ² floor area)	3586	1829	1721	376	893	269	3819	108
Average ceiling height (m)	2.4	1.8	2.7	3.0	9.1	3.0	101.5	3.0

ratio, the longer it takes for the virus concentration to reach its maximum (equilibrium value) and the lower the dose for that period. Thus subway cars and wide-body aircraft reach their maximum airborne virus concentration first, followed by

narrow-body aircraft, schools 9+, schools 3-8, the theater, the office and the stadium.

The ratio of viruses inhaled by groups of persons exposed for two hours to one ill person in narrow-body aircraft versus