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Inhalation of expiratory droplets in aircraft cabins

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Abstract Airliner cabins have high occupant density and long exposure time, so the risk of airborne infection transmission could be high if one or more passengers are infected with an airborne infectious disease. The droplets exhaled by an infected passenger may contain infectious agents. The present study developed a method to predict the amount of expiratory droplets inhaled by the passengers in an airliner cabin for any flight duration. The spatial and temporal distribution of expiratory droplets for the first 3 minutes after the exhalation from the index passenger was obtained using the computational fluid dynamics (CFD) simulations. The perfectly mixed model was used for beyond 3 minutes after the exhalation. For multiple exhalations, the droplet concentration in a zone can be obtained by adding the droplet concentrations for all the exhalations until the current time with a time shift via the superposition method. These methods were used to determine the amount of droplets inhaled by the susceptible passengers over a 4-hour flight under three common scenarios. The method, if coupled with information on the viability and the amount of infectious agent in the droplet, can aid in evaluating the infection risk.

Keywords: CFD, superposition, breathing, coughing, talking

Practical Implications: The distribution of the infectious agents contained in the expiratory droplets of an infected occupant in an indoor environment is transient and non uniform. The risk of infection can thus vary with time and space. The investigations developed methods to predict the spatial and temporal distribution of expiratory droplets, and the inhalation of these droplets in an aircraft cabin. The methods can be used in other indoor environments to assess the relative risk of infection in different zones and suitable measures to control the spread of infection can be adopted. Appropriate treatment can be implemented for the zone identified as high risk zones.

Introduction

A commercial air flight could last between 1 and 20 hours from gate to gate. During this time period, passengers are exposed to contaminants that may exist in the cabin air. This situation could become severe during the pandemic of a infectious disease, such as influenza, tuberculosis, or SARS, because the droplets exhaled by an index passenger with an infectious disease carry the

infectious agents (Cole and Cook, 1998 and Duguid, 1946) that can be inhaled by fellow passengers. However, the risk varies among the passengers. In addition to different immunities among the passengers, the exposure of each passenger to various infectious agents/droplets is also different because the airflow in an aircraft cabin is not perfectly mixed (Gupta et al., 2010a and Yan et al., 2009).

Our previous study (Gupta et al. 2010a) used a CFD model to simulate the temporal distributions of expiratory droplets for four minutes of real time from an index patient seated in the middle of a seven-row, twin-aisle, full cabin. The simulation took four weeks of computational time on an 8-parallel-processor computer cluster (total of two 2.33 GHz Quad-Core Intel processors and 16 GB memory). Therefore, it is not practical or feasible to perform the CFD simulation for a full-length cabin in 1 to 20 hours of flight time. Hence, it is necessary to develop a feasible method that can predict the exposure risk of each passenger in an airliner cabin due to the airborne infectious agents exhaled by an index passenger. Then possible mitigation methods could be developed to protect the passengers in the cabin.

Research methods and validation

This section first presents a brief summary of the CFD methods. The method to extend the data obtained from the 4 minutes of the CFD simulations (Gupta et al., 2010a) to whole flight duration as well as a method to quantify the number of droplets inhaled by the passengers is then presented.

This study used a seven-row, twin-aisle cabin mockup as an example for assessing the infection risk of the passengers caused by the infected passenger seated in seat 4D as shown in Fig. 1 (a). A tetrahedral mesh with a total of 1.5 million cells was used. A grid with 5 mm size on mouth, nose and face of the passengers, 20 mm size on the rest of the body of the passenger and seats, and 40 mm elsewhere was created. More than 98.5% of the cells had equi-size skew angle of less than 0.7. The Reynolds number based on the height of the cabin or half row width and supply inlet velocity was of the order of 4×10^5.

A commercial code, FLUENT was used to solve appropriate conservation equations for mass, momentum, energy, humidity, turbulence variables and expiratory droplet movement. The environmental variables solved were air velocity (all components), turbulent kinetic energy, turbulent dissipation rate, temperature, water vapor concentration, particle velocity, particle diameter and particle temperature. Zhang et al., 2009 and Zhang et al., 2007 found that the renormalization group (RNG) k-ε model (Yakhot and Orszag, 1986) can effectively predict the turbulent feature of the airflow in the aircraft cabins and other indoor environments. Therefore the RNG k-ε turbulence model was used for the investigations. The effect of temperature on density was considered along with the gravitational force to account for the buoyancy effects.

The expiratory droplets were tracked using the Lagrangian apporach. The Lagrangian approach incorporated in FLUENT as discrete phase modeling was used. The Discrete Random Walk model was used to account for turbulent dispersion of the particles (FLUENT, 2005). The point properties for the particles, which include the droplet size, injection time period, droplet temperature, total mass flow rate and velocities, were specified for the injections. The study used the flow boundary conditions obtained from the experiments (Gupta et al., 2009 and Gupta et al., 2010b) for the coughing, breathing, and talking processes. The investigations were performed

using mono-dispersed droplets for the coughing, breathing and talking cases. Therefore it was assumed that all the droplets exhaled during a particular exhalation were of one size. The dominating size for the droplets exhaled during the exhalation was used. For coughing, Yang et al., 2007 found that the average mode size of droplets exhaled was 8.35 μm. For breathing, Fabian et al., 2008 reported that the most of the droplets exhaled were between 0.3-0.5 μm. For talking, Duguid, 1946 reported a wide variation in droplet size spectrum and there was no single dominating size. The mean droplet size based on count and diameter was calculated and, was 30 μm. Therefore the size of droplets simulated for the coughing, breathing and talking exhalations was assumed to be 8.5, 0.4, and 30 μm respectively, which eventually reduced to 4, 0.19 and 14 μm due to evaporation (Gupta et al., 2010a). For the transient transport of droplets a time step size of 0.05s was used. For coughing period a time step of 0.001s was compared with 0.05s and no significant differences in the cough jet behavior were observed, therefore a time step of 0.05s can also be used for the exhalation period.

Droplet concentration around each passenger for any flight duration

The CFD simulations (Gupta et al. 2010a) showed that droplet distributions could be highly non-uniform in an airliner cabin. To assess the exposure risk of fellow passengers caused by the droplets exhaled by an index patient, it is important to know the actual number of droplets/infectious agents inhaled by each passenger. It is also important to know the time variation in the droplet concentration around the nose regions of the passengers. As passengers may move their heads, a zone of volume 0.0283 m^3 (1 ft^3) was constructed around the nose region of each passenger, as shown in Fig. 1 (b). The time variation of the droplet concentration in these zones was obtained using the CFD simulations (Gupta et al., 2010a).

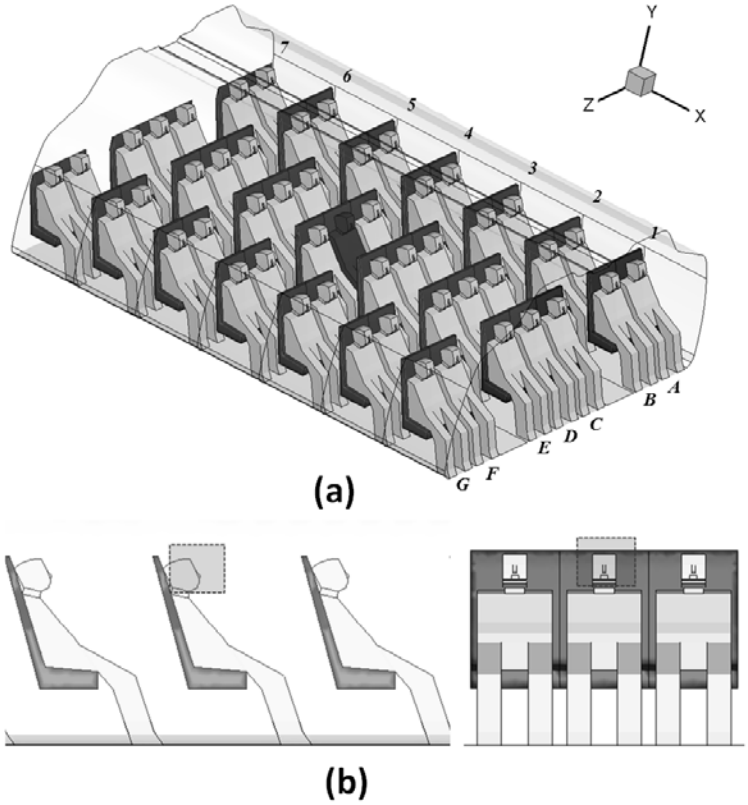


Figure 1. (a) Section of the seven-row, twin-aisle, fully occupied cabin used (Gupta et al., 2010a) (b) The zone of 0.305 m × 0.305 m × 0.305 m around the nose region of a passenger for determining the average droplet concentration

This study defined β (droplet fraction-s/m^3) as the average cumulative number of expiratory droplets in the vicinity of a passenger relative to the total number of droplets exhaled by the index passenger. The β was obtained by summing up the average droplet fraction over time and is given by equation (1).

$$\beta(t) = \sum \frac{N_i(t)}{vN_t(t)} \Delta t \qquad (1)$$

Where, v is the zone volume around the passenger, N_i the total number of droplets in the zone around the i^{th} passenger at time t, and N_t the total number of droplets exhaled for the exhalation of the index patient.

Figure 2 (a), (b) and (c) show the airflow in the cabin (Gupta et al., 2010a). The cold air from the supply inlets moved along the top wall and exited from the outlet located on the sides close to the base as shown in Fig. 2 (a). A part of this air moved to the center and rose up due to the natural convection created from the passengers seated at the center. This resulted in two re-circulation zones on both sides. The airflow around the index passenger seated on the center column (D) was towards the back and was natural convection dominated as shown in Fig. 2 (b), while the flow in the aisle was mixed as shown in Fig. 2 (c).

The expiratory droplet cloud from passenger 4D moved in the cabin with the bulk flow. The local droplet concentrations in the zones where the droplet cloud reached first were high, as the cloud was dense for the initial period. It was observed that the droplets eventually dispersed to all seven rows, but the droplet concentrations in the row furthest from the index passenger were relatively low. Therefore, the droplet concentration for the passengers seated only in the 3rd, 4th (index passenger), and 5th rows is discussed here.

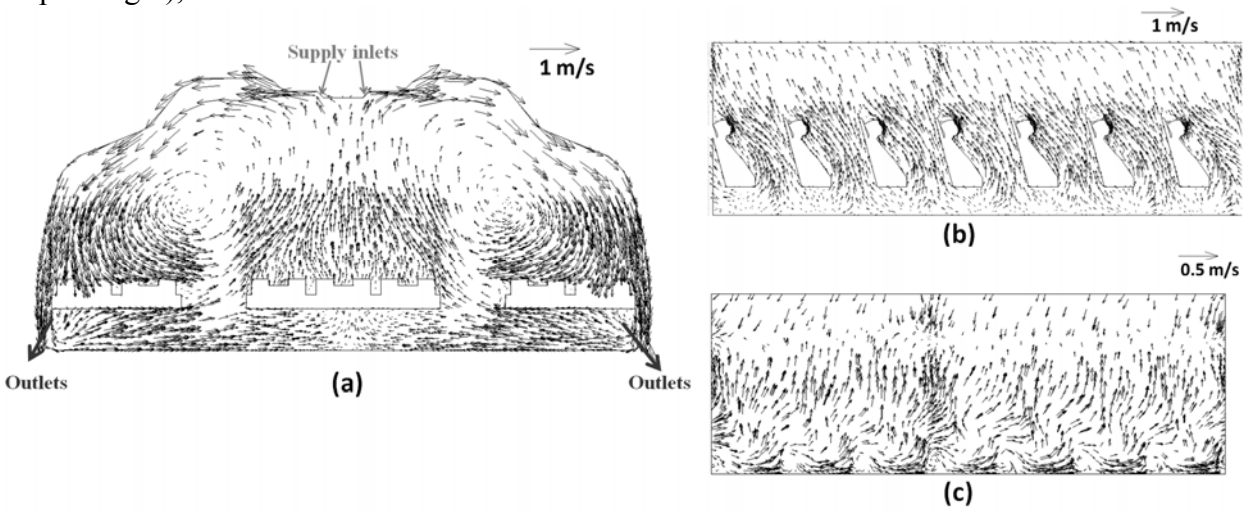
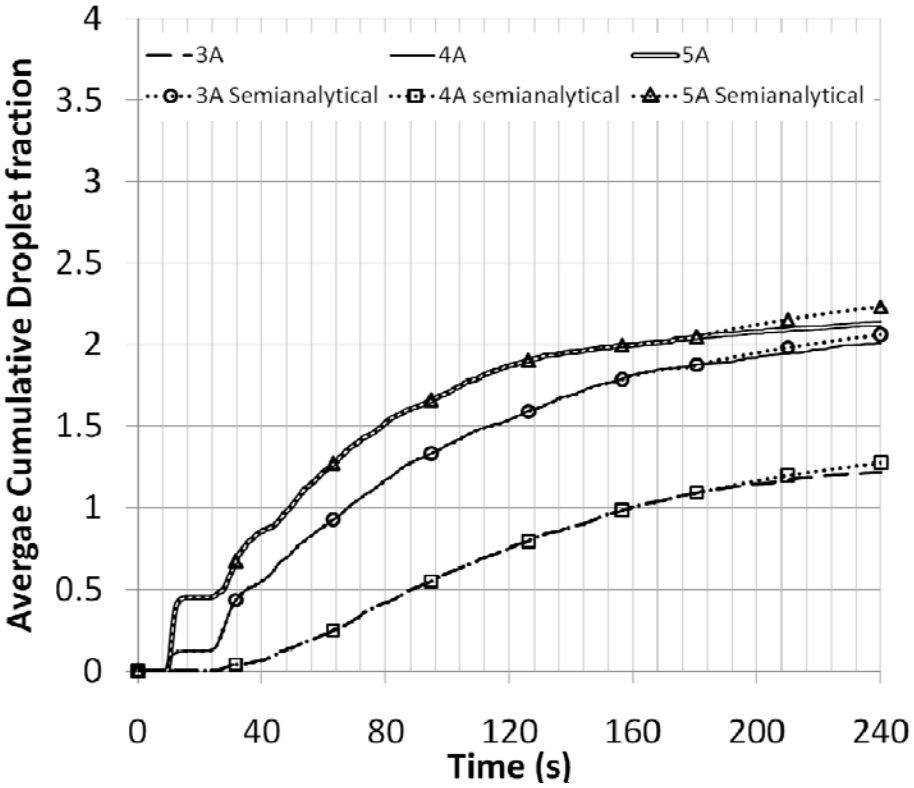
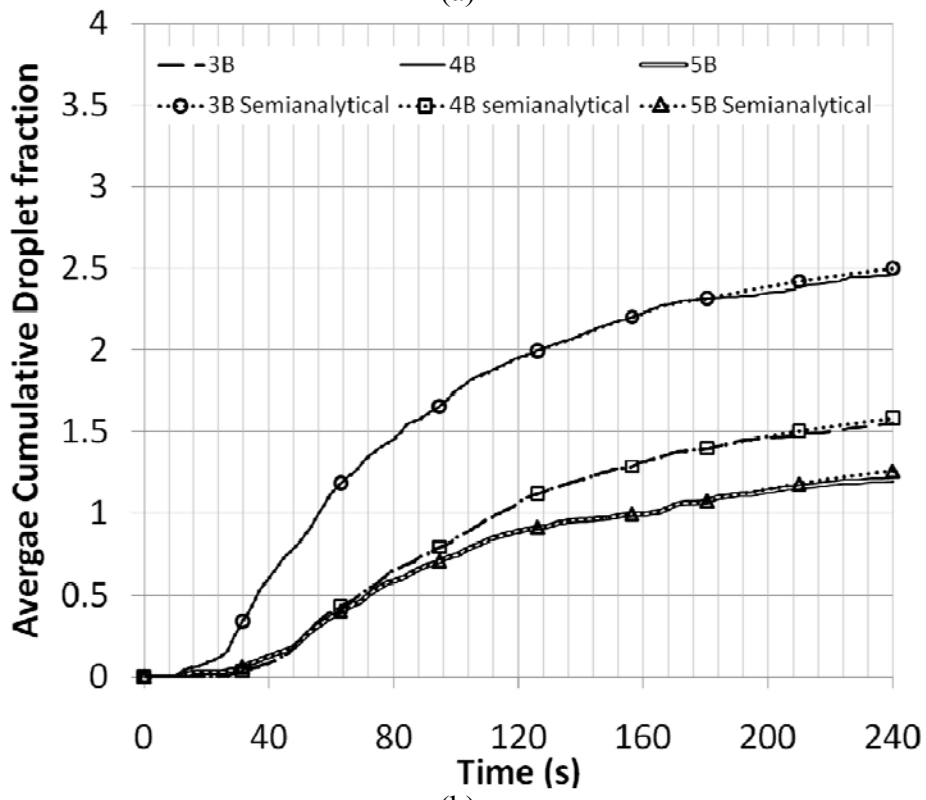


Figure 2. Velocity fields in the cabin on (a) cross section through the index patient (b) longitudinal section through the in dex patient (c) longitudinal section along the aisle (Gupta et al., 2010a).

Figure 3 shows the average cumulative droplet fraction (β) for the passengers seated in A (window), B (aisle), C (aisle), and D (center of the row) seats, respectively, for the expiratory droplets from a single cough by index passenger 4D. The droplets exhaled from the cough first moved to the front due to the high velocity of the cough jet. The droplets were small (8.5 μm, Yang et al., 2007) and were soon picked up by the bulk airflow. The bulk airflow around the index passenger as shown in Figure 2 (b) moved the droplet cloud upwards and to the back. The droplet cloud after reaching the top was picked up by the strong convective airflow as shown in Fig. 2 (a). The droplet cloud moved along the top wall towards the window and aisle seats (5A, 5B, 4A, and 4B) in about 10s. As the droplet cloud first reached these passengers, there was sudden increase in β for these passengers at around 10s as shown in Fig. 3. The rate of increase of β was higher for 5A and 4A as the droplets first passed through these zones. The droplet cloud then came to the lower zone in the aisle. The flow in the lower portion of the aisle was towards the front as shown in Fig. 2 (c), which made the droplet cloud move to the forward row. The droplet cloud then reached the passenger seated in 4C and dispersed in the 3rd, 4th and 5th rows. The rate of increase of β for the passengers seated in these rows was higher during the initial period (<1 min).


3A
4A
5A
3A Semianalytical
4A semianalytical
5A Semianalytical
Avergae Cumulative Droplet fraction
Time (s)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
40
80
120
160
200
240

(a)


3B
4B
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3B Semianalytical
4B semianalytical
5B Semianalytical
Avergae Cumulative Droplet fraction
Time (s)
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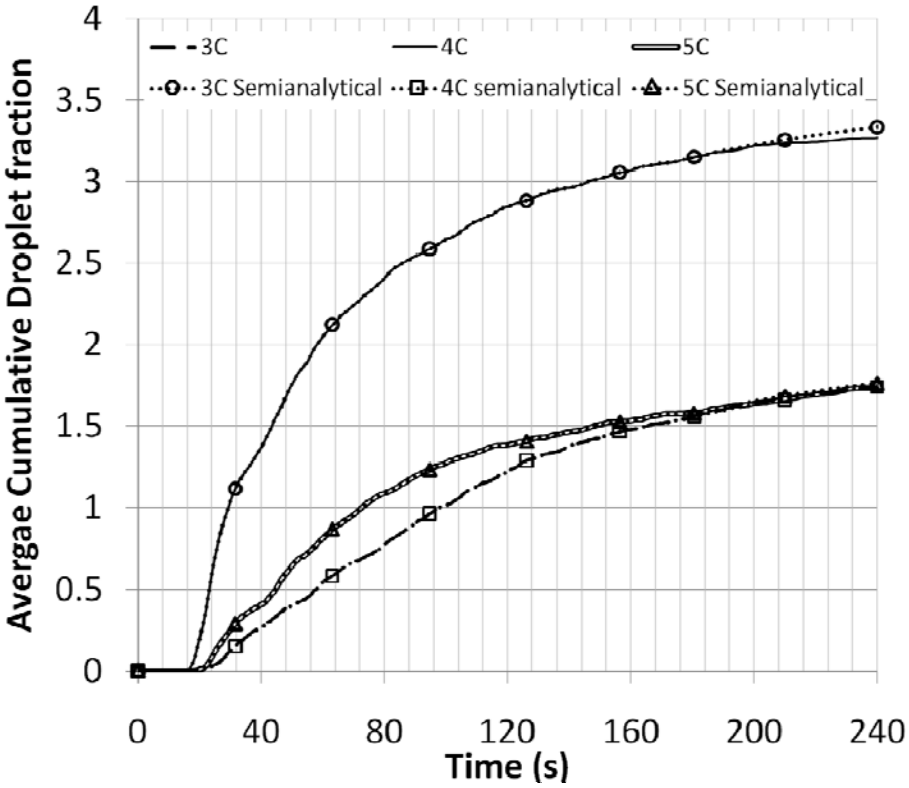
(b)


3C
4C
5C
3C Semianalytical
4C semianalytical
5C Semianalytical
Avergae Cumulative Droplet fraction
Time (s)
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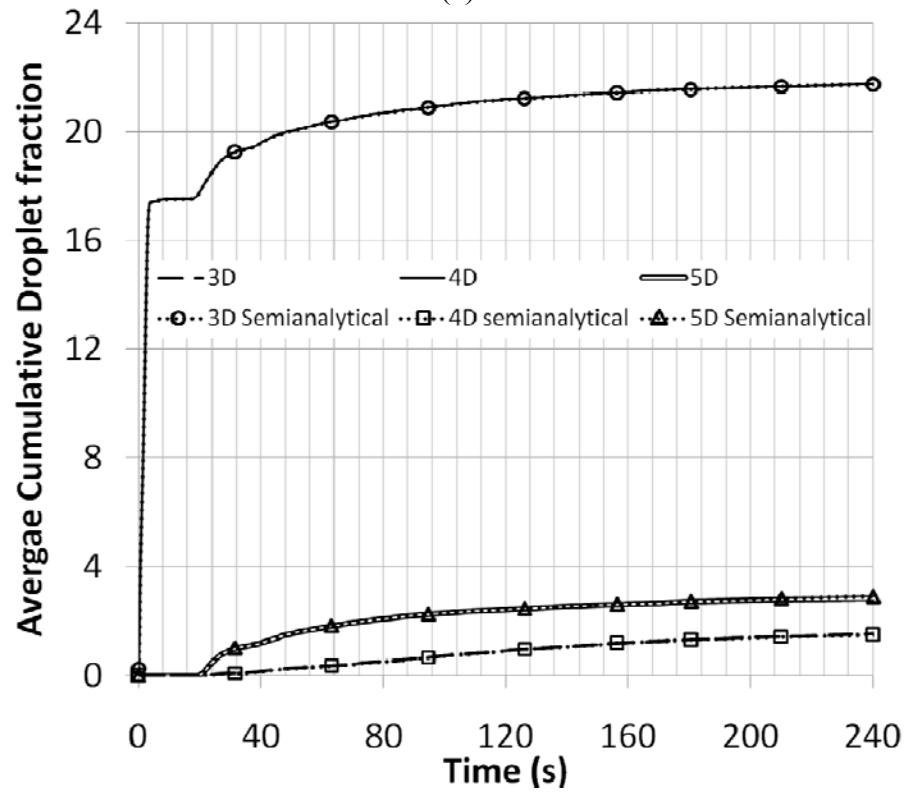
(c)


3D
4D
5D
3D Semianalytical
4D semianalytical
5D Semianalytical
Avergae Cumulative Droplet fraction
Time (s)
0
4
8
12
16
20
24
0
40
80
120
160
200
240

(d)

Figure 3. Average cumulative droplet fraction (β) over time for passengers due to a cough from the index passenger seat on (a) A seats (b) B seats (c) C seats (d) D seats

The droplets dispersed in the cabin in about 1 minute, but they did not perfectly mix in the cabin (Gupta et al., 2010a). In fact, Nazaroff et al. (1998) and Wan and Chao (2007) indicated that a perfectly mixed condition is merely an assumption and cannot be achieved. The variation in β clearly confirms that perfectly mixed conditions cannot be assumed for the initial (<1 min) period due to its sharp changes.

However, the increase in β after 3 minutes was steady and similar for the passengers. The droplets were found to disperse evenly in the cabin in three minutes (Gupta et al., 2010a). This indicates a state close to a perfectly mixed state. If perfectly mixed conditions could be assumed after 3 minutes (180s), the average droplet fraction concentration at any point can be written as

$$c(t) = \frac{n_t(180)\exp(-Q(t-180)/V)}{V} \qquad (2)$$

where $n_t(180)$ is the total droplet fraction at 180 s, i.e., the total number of droplets in the cabin at 180s divided by the total number of droplets exhaled, Q is the total supply flow rate to the cabin, and V is the volume of the cabin.

Therefore, a semi-analytical approach can be adopted to obtain the average droplet fraction (c(t)) in the vicinity of the passengers. The CFD simulation can be used to obtain the c(t) for the first 3 minutes after the droplet release and equation (2) to obtain c(t) beyond 3 minutes. It should be noted that the average droplet fraction given by equation (2) is also the rate of increase in the average cumulative droplet fraction (β). Figure 3 compares β(t) calculated using the semi-analytical approach with the CFD simulations for t>3 minutes. The differences were smaller than 10% and therefore perfectly mixed method can be used for t > 3 minutes with 10% uncertainty. Hence, one can use the CFD methods to obtain the droplet concentrations around the passengers for the initial period of 3 minutes and equation (2) for beyond 3 minutes.

Although not presented here in detail, one can expect that the β for the droplets from the breathing and talking of passenger 4D could be different from those of coughing, but the method developed above can be used for breathing and coughing.

Droplets inhaled by a passenger due to multiple exhalations from the index passenger

An index passenger normally exhales droplets through multiple events, such as combined breaths, coughs, and talking. To carry out CFD simulations for such combined events can be very time consuming. Thus, it is important to further develop the above semi-analytical method for the multiple exhalations from the index passenger.

This investigation started from using continued breathing as an example. An unsteady CFD simulation was carried out for a case with 10 consecutive exhalations from the normal breathing of index passenger 4D. The turbulent flow and the breathing of the passengers made the local airflow in the cabin unsteady. However, the droplets from all the exhalations followed similar trajectories, even though the airflow in the cabin was unsteady. This indicates that the bulk flow in most of the domain was almost steady. Therefore, the information on the droplet concentration obtained using the CFD simulations for a single breath exhalation from the index

passenger can be superimposed multiple times to obtain the droplet concentration in the cabin for the multiple exhalations of the index passenger by the following equation:

$$C_i(t) = \sum_{\text{For all } j} C_{b,i}(t - t_j) \quad (3)$$

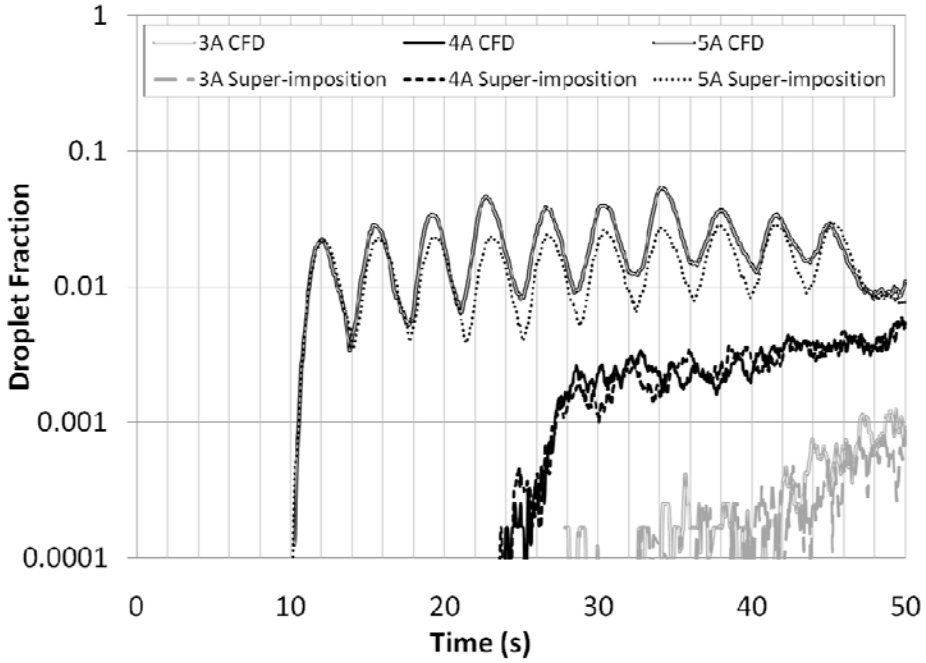
Where, $C_i(t)$ is the average droplet concentration in the breathing zone of the i^{th} passenger at time t and $C_{b,i}(t\text{-}t_j)$ is the average droplet concentration in the zone at time $t\text{-}t_j$ due to the breathing started at t_j, and can be obtained from the CFD simulation for the single breathing exhalation case. All the breathing exhalations that have happened until time t should be summed.

If the principle can be extended for coughing and talking, the droplet concentration in a breathing zone can be obtained by summing up that from all the exhalations taking place until current time with a time shift:

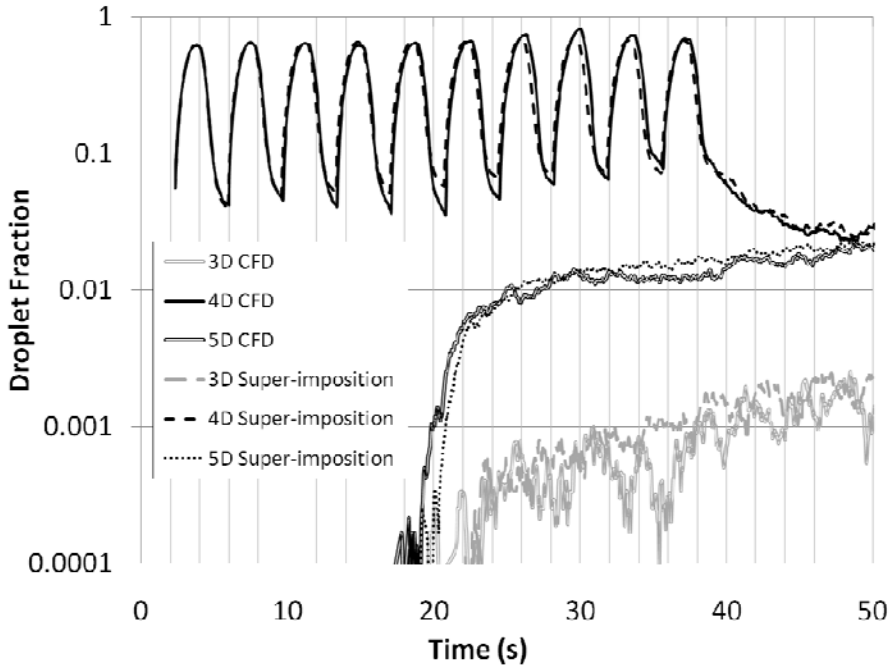
$$C_i(t) = \sum_{\text{For all } m} C_{c,i}(t - t_m) + \sum_{\text{For all } j} C_{b,i}(t - t_j) + \sum_{\text{For all } k} C_{ta,i}(t - t_k) \quad (4)$$

where $C_{c,i}(t\text{-}t_m)$ is the average droplet concentration in the breathing zone at time $t\text{-}t_m$ due to the coughing starting at t_m, and $C_{ta,i}(t\text{-}t_k)$ is the average droplet concentration in the zone at time $t\text{-}t_k$ due to the talking starting at t_k. All such exhalations (coughs, breaths or talks) that have happened until time t should be summed. The $C_{c,i}$, $C_{b,i}$, and $C_{ta,i}$ can be obtained from the CFD simulations for the droplets exhaled from a single cough, breathing, and talking, respectively.

To evaluate the developed model, Figure 4 compares the droplet fraction in the breathing zones with 10 consecutive exhalations from the index passenger predicted by CFD with the droplet fraction calculated by the superposition method. The variation trend of the droplet fraction was similar for the two methods. The differences in the absolute values of droplet fractions for the neighboring passengers were within ±0.03. The differences could be attributed to the inherent flow transience and the transient breathing. The high frequency variations were very difficult to capture by the simplified superposition method. Figure 5 further compares the β predicted by the two methods. Again, the two methods yielded very similar results. Thus, this investigation used the superposition method for further analysis.



(a)



(b)

Figure 4 A comparison between the droplet fraction predicted by the CFD model and the superposition method for passengers seated in (a) 3A, 4A, and 5A seats and (b) 3D, 4D, and 5D seats.

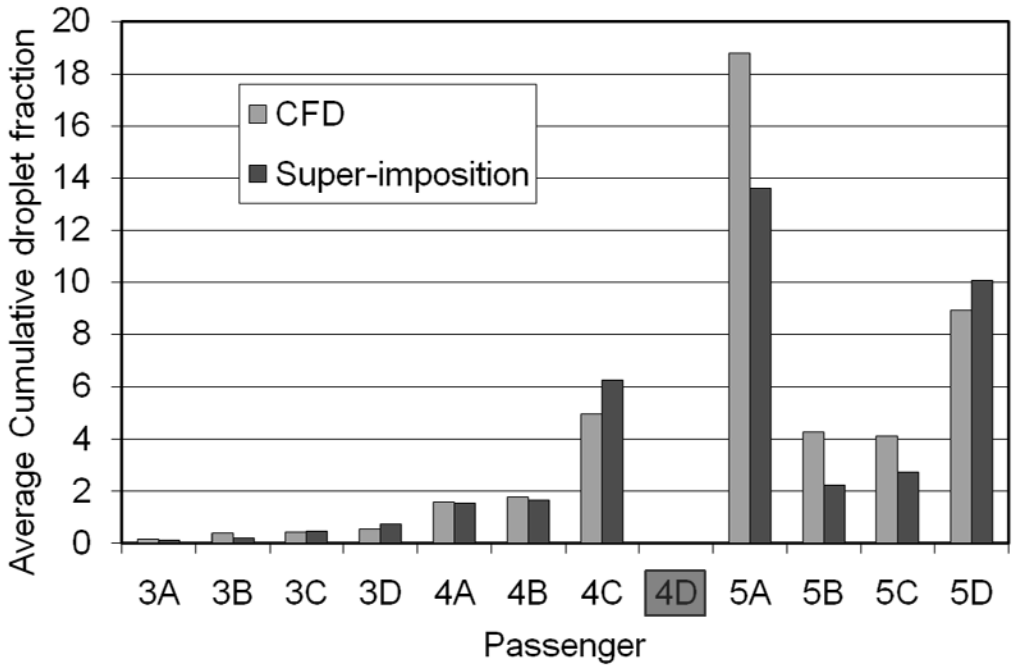


Figure 5. A comparison of the β *predicted by the CFD and superposition methods for passengers sitting in the 4th , 5th , and 6th rows.*

The total amount of droplets inhaled by each passenger can be calculated by summing up the breathing profile of each passenger with the droplet concentration in the breathing zone:

$$r_i(t) = \sum q_i(t) C_i(t) I_f \Delta t \qquad (5)$$

where q_i is the rate of inhalation (volume/time) for the i^{th} passenger and is zero during exhalation, and C_i is the average droplet concentration (number of droplets/volume) in the zone around the i^{th} passenger. Gupta et al. (2010b) showed how to obtain q_i based on the physiological details of the passengers. I_f is the inhalability fraction, corresponding to the droplet size. The inhalability fraction of a particle can vary with the particle size, ambient wind speed and direction and breathing mode and rate (Milage et al., 2010). As the velocity of wind around the passengers in the cabin was under 1 m/s, the modified correlation of Menache et al., (1995) and Milage et al. 2010 was used to obtain the inhalability fraction. It is given by equation (6); where, d_{ae} is the droplet diameter in micrometers.

$$I_f = 1 - \left(\frac{1}{1 + 6.809 \times 10^3 d_{ae}^{-2.736}} \right) \qquad (6)$$

Figure 6 shows a representative variation of the cumulative droplets inhaled by a passenger, the droplet concentration in the breathing zone, and the breathing flow rate. The droplets inhaled by the passenger were zero initially as the droplet concentration in the breathing zone was zero. The droplets inhaled by the passenger increased during the inhalation period and remained at that value for the next exhalation. It should be noticed that the amount of droplets inhaled varied with the inhalation. It was due to the phase difference between the breathing wave and the droplet concentration around the passenger, which kept on changing. The amount

inhaled over each inhalation would have remained the same if the passenger had the same breathing frequency as the index passenger. In order to avoid such a situation, we have used asynchronized breathing patterns, with different breathing frequency and amplitude of the breathing sinusoidal wave for the passengers. Moreover, as the amount of droplets inhaled can vary with the inhalation, it is required to calculate the amount of droplets inhaled over a significant span of time so that the average value of the droplets inhaled for the passenger does not change. We have noticed that the amount of droplets inhaled over 4 hours of time was twice the amount of droplets inhaled over 2 hours of time (differences within ±0.5%) for the passengers.

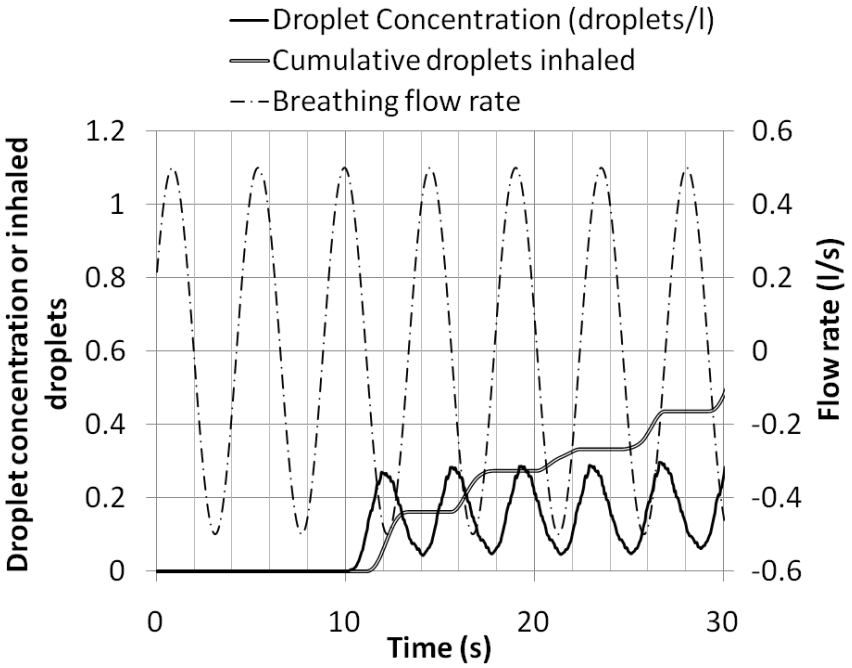


Figure 6. A representative variation in droplet fraction and the cumulative droplets inhaled

Case setup

With the method to extend the CFD data of 3 minutes to the whole flight and the method of superposition to calculate the droplet concentration in the breathing zones, this investigation has studied the droplets inhaled by different passengers in the cabin shown in Figure 1 during a 4-hour flight. Since the index passenger can exhale droplets through coughing, breathing, talking, or any combination of these exhalations, three hypothetical cases were analyzed and are as follows:

1) Breathing only: This case assumed that the index passenger exhaled 525 droplets for every breathing exhalation, as calculated by Gupta et al., (2010a) using the measurements performed by Fabian et al., (2008) and Edwards et al., (2004) on the amount of droplets exhaled during breathing. It should be noticed that the methods developed are based on the droplet fraction (non-dimensionalized with the amount of droplet exhaled) and therefore, do not depend on the number of droplets exhaled. The number of droplets exhaled was considered to illustrate the method to evaluate the amount of droplets inhaled.

2) Coughing and breathing: The studies by Hsu et al. (1994) and Loudon and Brown (1967) indicated that the cough frequency can vary from 12 to 35 and 3 to 48 coughs per hour, respectively. By using an average from these studies, this case assumed 100 coughing exhalations for the 4 hour flight. Since the index passenger would also breathe normally, the 100 coughing exhalations were randomly sandwiched between the breathing. It was further assumed that the index passenger exhaled 10^6 droplets for each cough, as measured by Yang et al., (2007) and Hersen et al., (2008) for healthy and symptomatic human subjects.
3) Talking and breathing: This case assumed that the index passenger would talk for 30 minutes during the flight. The talking exhalations were also coupled with the breathing exhalations. It was assumed that the index passenger released 150 droplets every second through the talking, as calcualted by Gupta et al., (2010a) using the studies of Fairchild and Stampfer, (1987).

Results

Figure 7 presents the total amount of droplets inhaled by the fellow passengers due to the exhalations from index passenger 4D for the three cases by using the research method developed and validated in the previous section. The results are for passengers seated on the 3rd, 4th, and 5th rows. The number of droplets inhaled by the index passenger is not shown as it is not meaningful. The inhaled droplets varied with location and type of exhalation from the index passenger.

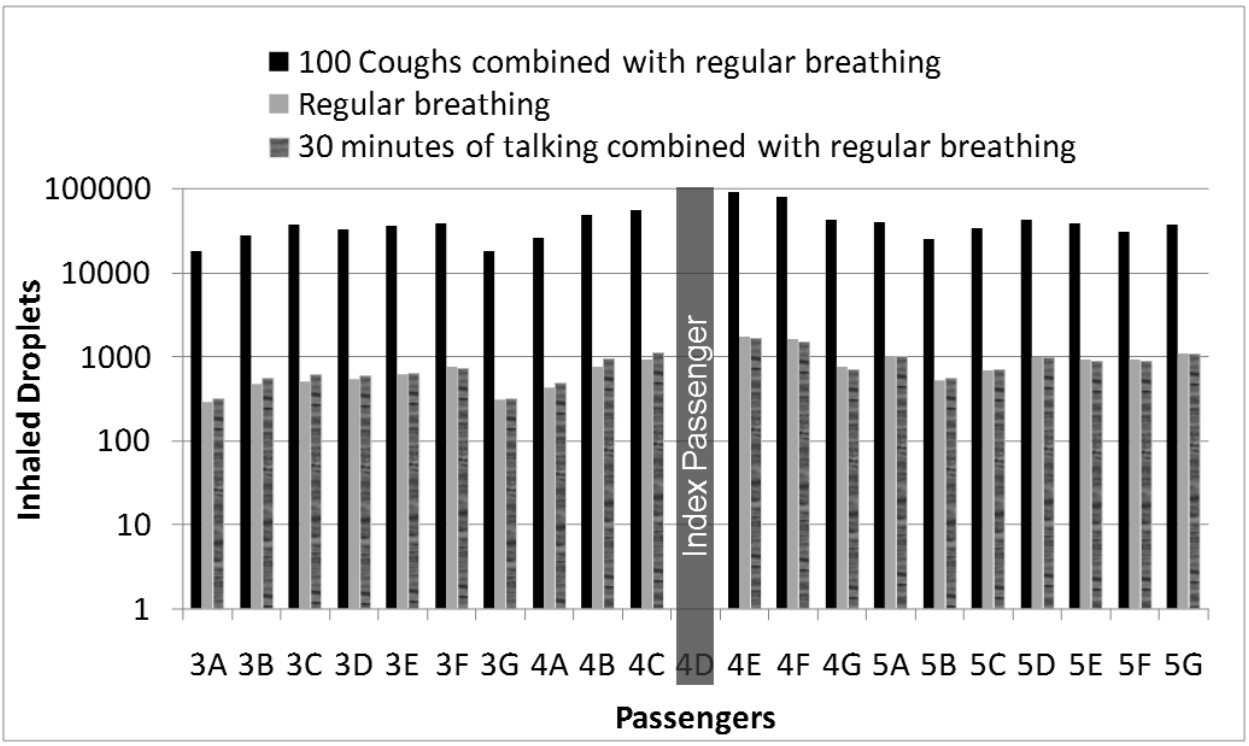


Figure 7. The droplets inhaled by the passengers seated in the 3 rd, 4th and 5th rows for regu lar breathing, 100 coughs combined with regular br eathing, and 30 minutes of talking along with regular breathing by the index passenger for the 4 hours of flight.

The droplets inhaled by these passengers, generated by the exhalations from the regular breathing of the index passenger, varied from 300 to 2000 depending on the movement of the droplets. The droplets first went to passenger 5A and 5G but stayed there only for a short period of time due to the high air velocity in that zone. These droplets then went to passengers in 4C, 4D, 4E, 5C, 5D and 5E; thus, the number of droplets inhaled by these passengers was high. The droplet cloud reached the 3rd row after some time, then the droplet concentration decreased, so the number of droplets inhaled by passengers seated in this row was relatively low. It should also be noticed that the amount of droplets inhaled was not symmetric about the index passenger. This is due to the local un-symmetry in the flow caused by the combined effects of instability caused by the thermal plume, forced convection and turbulent nature of the flow.

When the coughing was combined with regular breathing, the droplets inhaled by the fellow passengers varied from 18000 to 90000. This was because a cough contains 10^6 droplets, while a breath contains only 525. Clearly, the exhalation from a cough carries more risk to fellow passengers than the breathing. The droplets inhaled by passengers in 5A, 5G and 5D were relatively fewer than those inhaled by the passengers in row 4. This is because the high velocity of the cough jet pushed the droplets to the front of the index passengers, so fewer droplets moved to the back row (5th row) (as discussed in the last chapter).

For the case in which talking was combined with regular breathing, the droplets inhaled by the fellow passengers varied from 300 to 1700. The talking exhaled droplets inhaled by the passenger in 4C were relatively more than those inhaled by the other passengers because the passenger was in conversation with the index passenger. The droplets inhaled by the passengers and the distribution pattern were similar to the case that had only breathing. This implies that the rate of release of droplets from talking was similar to rate of release from breathing. As the combined effect of breathing and talking is shown, the order of effective amount of droplets inhaled is a cumulative of both the processes.

It was observed that the number of droplets inhaled was linear with time. Our calculations for 2 hours of flight durations showed that the amount of droplets inhaled were half the amount of the droplets inhaled for 4 hours of flight for all the passengers (within ±0.5% differences).

Discussion

The study proposed a method to determine the amount of droplets inhaled by the passengers over a realistic flight time. The amount of droplets inhaled was calculated using the spatial and temporal distribution of the expiratory droplets. The expiratory droplet movement was in accordance with airflow, and the airflow predictions were in agreement with the studies by Zhang and Chen (2007) and Zhang et al., (2009). It is required to conduct controlled experiments to validate the quantitative predictions on the expiratory droplet distribution. The validation can be helpful in improving the developed CFD methods.

Regarding the accuracy of the turbulence model, Zhang et al., 2007 found that the relative error in the mean velocity, temperature and turbulence parameter predicted by the RNG k-ε model was less than 20-30%, 10% and 20-30% respectively at most of the points. Regarding

the accuracy of the particle tracking model, Zhang et al., 2009 compared the steady state particle concentration against the experiments and found that the agreement was reasonable.

The study developed methods by considering an economy class twin aisle passenger airliner cabin. The airflow and the droplet distribution can change with the cabin configuration such as the passenger class, seat region, and the location of supply air and exhausts. The study assumed that all the passengers were seated all the time during the flight under a ventilation rate of 33.7 ACH. The study does not account for the inevitable movement of the passengers that can influence the particle transport (Desenclos et al., 2004; Ooi et al., 2009 and Poussou et al., 2010). The ventilation rate can vary based on take-off, landing, and cruising (Mangili and Gendreau, 2005); this may influence the particle transportation. This can influence the risk prone zone and therefore, appropriate care must be taken in extending the analysis presented in the paper to other situations.

We could not investigate the transport of droplets from the sneeze of an infected person, as the flow boundary conditions for sneezing were unavailable. Sneeze could be an important source of infectious agents/droplets and should be studied for its role in transmitting airborne infectious diseases.

The equation developed to calculate the amount of droplets inhaled by the passengers should be used either over significant span of time or if the exact information on the breathing pattern is available. In absence of such information, the equation can still be used but the sinusoidal breathing function should be replaced with an average breathing flow rate for the passenger.

The investigation calculated the droplets inhaled by the passengers sitting in the same row as the index passenger and then in the neighboring rows, for three common scenarios. The droplets inhaled by the fellow passengers were of the order of 10^3 due to the breathing and talking in the 4-hour flight and 10^5 due to the coughing. It should be noted that not all these droplets contained active infectious agents. The study provided only an estimate of the relative risk of infection to the passengers.

The information on the viability and the amount of the infectious agents should be added to our model to predict the spatial distribution of infection risk in the cabin. The model accounts for the time and spatial variation of parameters such as the breathing flow rate and the droplet concentration. The model can be easily coupled with the viability and amount of infectious agents. Some information is available from the literature concerning the viability of infectious agents (Tang, 2009; Arundel et al., 1986; Wright et al., 1968 and Harper, 1961) but only a few studies have been done that quantify the number of infectious agents in breathing (Stelzer et al., 2009; Fabian et al., 2008, 2009; Milton et al., 2010 and Huynh et al., 2008), coughing (Milton et al., 2010 and Fennelly et al., 2004), or talking.

Fabian et al., (2009) indicated that an influenza-infected subject can exhale 0.01 to 2 influenza virus ribonucleic acid (RNA) particles per minute (geometric mean 0.1) through breathing. The amount of such influenza virus RNA particles for a cough combined with 1 minute of breathing ranged from 0.1 to 20000 per minute (geometric mean 3.1) and 0.1 to 100000 per minute (geometric mean 5) for coarse and fine particles, respectively (Milton et al., 2010). Therefore, a cough alone can contain 8 (geometric mean) influenza virus RNA particles. It should be noted that the influenza virus RNA particles is a measure of viral nucleic acid and could be derived from the infective and non-infective viruses. A case with an index passenger infected by influenza was analyzed, using this data, using the influenza virus RNA particles

exhaled from the coughing and breathing. The geometric mean and 95% confidence bounds for the amount of influenza virus RNA particles were used. It was assumed that the influenza virus is viable for 4 hours under the cabin ambient conditions (Harper et al., 1961). Figure 8 shows the amount of influenza virus RNA particles inhaled by the fellow passengers for the breathing only case as well as for the combined coughing and breathing case. The amount of inhaled influenza virus RNA particles for the coughing combined with the breathing case was higher than in the breathing only case. The influenza virus RNA particles inhaled were few and may not be enough to cause infection. The droplets inhaled were much higher in number than the influenza virus RNA particles. Thus, appropriate care must be taken when extending the information on the droplets inhaled to the infection risk.

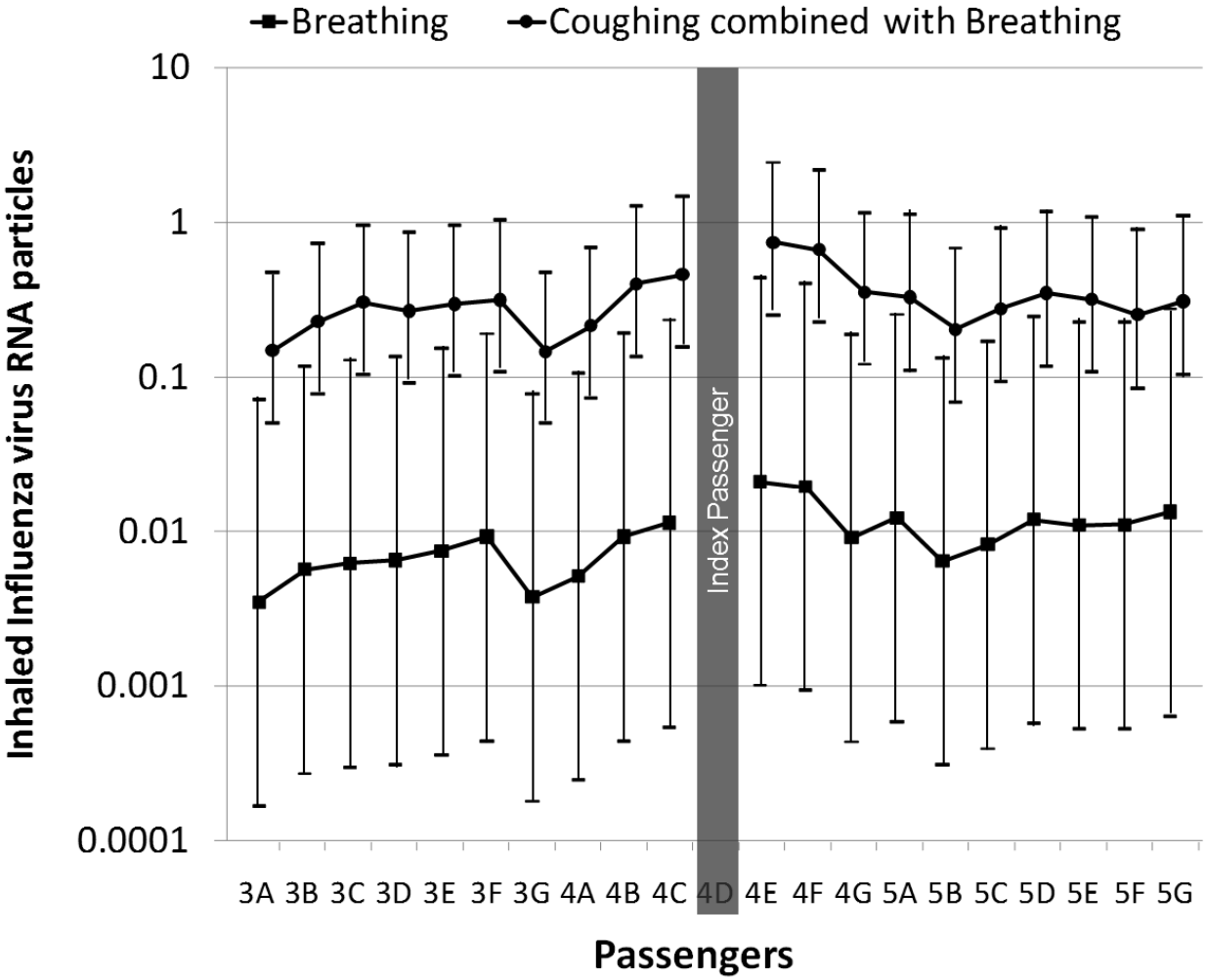


Figure 8. Influenza virus RNA particles inhaled by fellow pa ssengers due to only breathing and 100 coughs combined with regular breathing from the index passenger for the 4-hour flight

Conclusions

The investigation developed a method to predict the transport of droplets exhaled from combinations of breathing, talking, and coughing of an index passenger in an aircraft cabin for

the whole flight duration. Since the droplets were well mixed in the cabin air after they were released for 3 minutes, the method used combined CFD and mixed condition models for the prediction. The droplets from multiple exhalations can be superimposed to obtain their transport. The droplets inhaled by a passenger can consequently be determined for the whole flight duration.

This study further determined the number of droplets inhaled by fellow passengers due to the droplets exhaled from regular breathing, 100 coughs sandwiched with regular breathing, and 30 minutes of talking combined with regular breathing from the index passenger in a 4-hour flight. The risks to the passengers can be calculated by combining this information on the amount of droplets inhaled with the infectious agents contained in the exhaled droplets, and appropriate risk assessment model. As the amount of droplets inhaled by the passengers for the coughing case was higher, the risk to the fellow passengers will be higher if the droplets contained active infectious agents. The infection risk can be quantified using the information on the inhaled dose in an appropriate risk assessment model.

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