Controlling outdoor and indoor spread of COVID-19

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Contents

1 Outdoor transmission of COVID-19

1.1 (a) Temporal evolution of the virus concentration at head height at viewing platforms 1, 3, 7, and 13

To calculate the concentration of SARS-CoV-2 virus at each of the viewing platforms, the virus is considered to be released by the concert-goers in platform 13 as a **point, continuous, 3D release**. As a result, the concentration is obtained by using the following governing equations for point, continuous, 3D diffusion release:

$$C = \frac{\dot{M}}{4\pi D_t r} erfc(\frac{r}{\sqrt{4D_t t}}) \tag{1}$$

However, the virus paticles are also reflected when it hits the boundary, which is the ground surface (z=0). As a result, an image source needs to be introduced. Thus, the equation used to calculate the virus concentration at different viewing platforms are:

$$C = \frac{\dot{M}}{4\pi D_t r} erfc(\frac{r}{\sqrt{4D_t t}}) + \frac{\dot{M}}{4\pi D_t r_2} erfc(\frac{r_2}{\sqrt{4D_t t}}) \tag{2}$$

Where radius, r, of the viewing platforms calculated can thus be calculated by $\sqrt{dx^2 + dy^2 + dz^2}$, considering the x and y coordinates of the viewing platforms tabulated below and r_2 is radius from reflector surface (the ground), where $r_2 = \sqrt{(dx^2 + dy^2 + (dz - 2h)^2)}$.

In this scenario, M is taken as $\frac{98}{3600} * 4$, in line with the estimates of Quanta emission rate of speaking loudly/singing, D_t is assumed to be 1 $m^2 s^{-1}$, and every concertgoers have the same height (1.8m). The coordinates of viewing platforms 1, 3, 7, and 13 are tabulated below.

Viewing Platforms	Coordinates (x,y)
1	(-8,8)
3	(0,8)
7	(-4,4)
13	(1,1)

Applying equation 2 on coordinates of viewing platforms 1, 3, 7, and 13, the temporal evolution of the concentration of the virus can be obtained. This temporal evolution is plotted in a loglog graph, which shows its evolution over the duration of the concert.

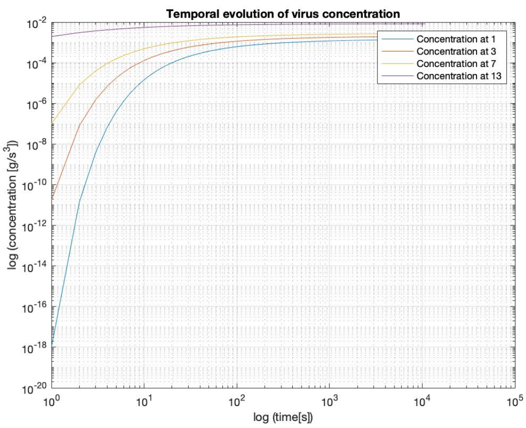

Figure 1: Temporal evolution of virus concentration

From the plot, the virus concentration starts to flatten out and remains more constant as t increases. This is because as t approaches ∞, the $erfc(\frac{r}{\sqrt{(4D_t t)}})$ component of equation (2) approaches 1. As a result, when $t = \infty$, $C = \frac{\dot{M}}{4\pi D_t r} + \frac{\dot{M}}{4\pi D_t r_2}$ and suggests that steady state has been reached.

Furthermore, it is shown the closer the viewing platforms are to the people infected by the SARS-CoV-2, the higher the initial concentration of the virus. However, the difference in concentration of the decreases over time.

In a stationary fluid, the transportation of the virus is primarily due to molecular diffusion. Molecular diffusion is a result of existence of a gradient of concentration within the fluid, and thus it tends to equalise the distribution over the whole volume. This is also known as **Fickian diffusion**, which is governed by Fick's Law (Paradisi et al. 2001). As the virus spreads, the gradient of concentration decreases and the concentration of virus will be largely distributed equally over the whole volume.

Fick's Law states that the flux of solute mass in a given direction is proportional to the gradient of the solute concentration in that direction, such that

$$\vec{q} = -D\nabla C \tag{3}$$

In this scenario, the diffusion coefficient D_t is taken as 1 m^2/s, which is much higher than diffusion coefficient of CO_2 in air (1.37 x 10^{-5} m^2/s). This results in the virus to be modelled to have spread rapidly in the concert ground during the duration of the concert. While this is a conservative way to consider the 'worst case scenario' where the virus diffuse at a very rapid rate, this creates major inaccuracy and overestimation of temporal evolution of concentration of virus in the concert ground in the results. A research by Zhdanov & Kasemo (2020) suggests that the more accurate value for D would be in the region of 10^{-5} to 10^{-6}, based on particle size of SARS-CoV-2 of approximately 100nm.

Moreover, diffusion coefficient, D, represents a value specific to chemical and environment. As research on the chemistry of SARS-CoV-2 virus particle is ongoing, it is difficult to accurately obtain a specific D value for the virus. Moreover, D also depends on temperature, as it is associated with molecular processes. In the United Kingdom today, temperature is relatively lower outdoor, thus reducing the value of D. The effects on mask-wearing on the value of D should also be explored further to determine the best settings for resumption of public activities.

In conclusion, while the result above shows the spread of SARS-CoV-2 virus based on $D_T = 1$ m^2/s, this result is likely an overestimation of the virus spread, due to the inaccuracy in the value of D_T used. Thus, if social distancing is possible, outdoor activity with duration less than a certain hours should be allowed to continue. This is in line with government regulation effective 2 December 2020 in England, where public attendance at outdoor and indoor events (spectator sport, business events, performances and shows) is permitted at areas under tier 1 and tier 2 restrictions, albeit initially with limited attendance capacity.

1.2 (b) Spatial distribution of the virus concentration

At the end of the concert (t=3 hours), the concentration of the virus in the no wind condition can be modelled by equation (2), as it is only spreading by diffusion. However, with a 3m/s wind from the south-west, the virus will also spread by advection. Thus, for this condition, the virus concentration will be governed by 3D continuous release advection-diffusion equation below, assuming that at t=3 hours, steady state has been reached.

$$C = \frac{\dot{M}}{4\pi Dr} e^{-\frac{U}{2D}(r-x)} \tag{4}$$

Adding the reflector term due to the plane solid boundary in the ground surface,

$$C = \frac{\dot{M}}{4\pi Dr} e^{-\frac{U}{2D}(r-x)} + \frac{\dot{M}}{4\pi Dr_2} e^{-\frac{U}{2D}(r_2-x)} \tag{5}$$

Applying equations (2) and (5) on all coordinates where $x, y \in [-9, 9]$, contour plots can be obtained. Results within radius of 1 from the centre has been removed as the person who releases the virus moves about their viewing platform.

From the contour plots above, the two conditions show similarities. Both the contour plot show that the virus concentration is spreading and dilluting from the continuous point of release (0,0). This spread is a result of diffusion, which causes dilution of the virus particle in the surrounding fluids. This spread is primarily governed by Fick's Law, and due to the difference in the concentration of virus contamination in the fluids within the concert ground volume.

However, the difference in the contour plot above is that when there is a 3m/s wind blowing from the South-west, there is advection effects on the transport of the virus particle. It can be observed that the virus particle moves towards the stage.

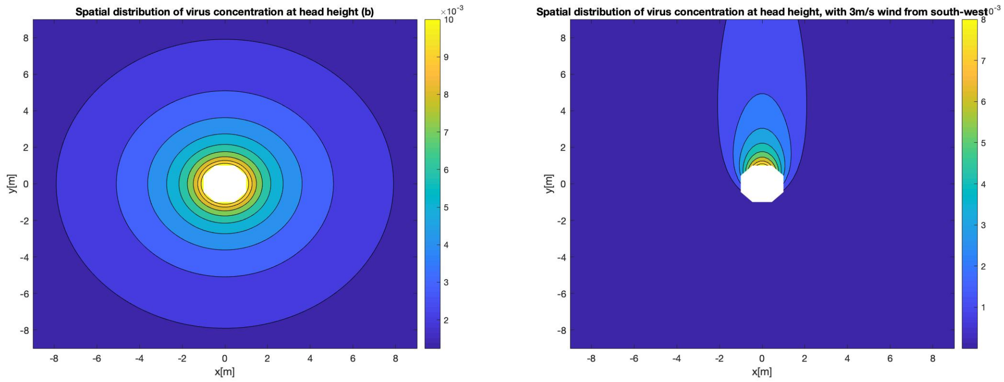

Figure 2: End of concert spatial distribution of virus concentration at no wind condition (left) and 3m/s south-west wind condition (right)

The measurement of how dominant advection is over diffusion can be obtained by Péclet number, which is given by

$$Pe = \frac{advection}{diffusion} = \frac{U_0 L_0}{D} \tag{6}$$

1.3 (c) Virus concentration with disinfectant applied

When sufficient disinfectant can be aplied to all ground surfaces within the public area prior to the concert so as to kill the virus upon contact for the duration of the concert, another boundary condition emerges at the ground surface solid plane boundary. As the ground surface becomes a perfect absorber of the virus particle, the Dirichlet boundary condition applies, and C = 0. Image source of opposite strength (a sink) is then introduced and the following equation applies for no wind condition (diffusion only).

$$C = \frac{\dot{M}}{4\pi D_t r} erfc(\frac{r}{\sqrt{4D_t t}}) - \frac{\dot{M}}{4\pi D_t r_2} erfc(\frac{r_2}{\sqrt{4D_t t}}) \tag{7}$$

For the condition when the wind is blowing at 3m/s from South-west, the same concept applies and the following equation applies.

$$C = \frac{\dot{M}}{4\pi D r} e^{-\frac{U}{2D}(r-x)} - \frac{\dot{M}}{4\pi D r_2} e^{-\frac{U}{2D}(r_2-x)} \tag{8}$$

Applying equations (5) and (6), the spatial distribution of the virus concentration can be obtained.

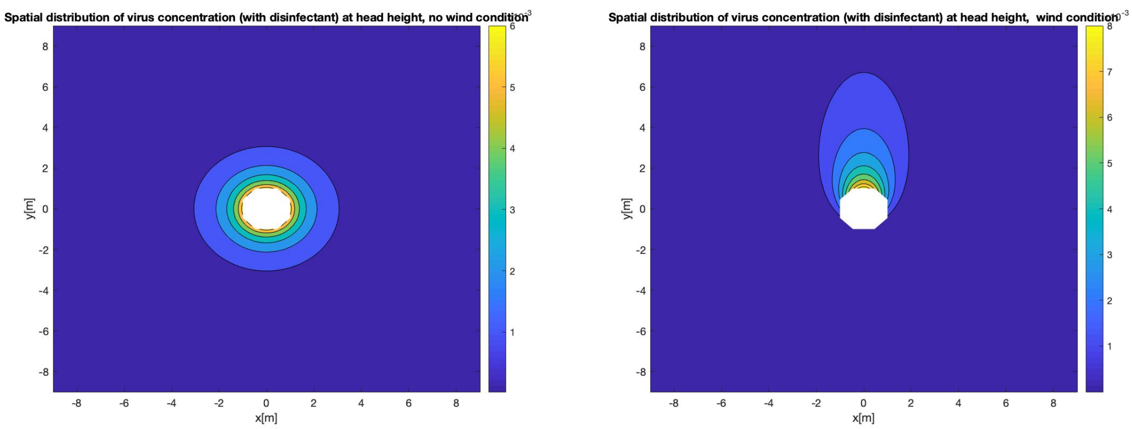

Figure 3: End of concert spatial distribution of virus concentration with no wind condition (left) and 3m/s south-west wind condition (right) with disinfectant

Comparing the virus concentration on Figure 2 and Figure 3, the changes in virus concentration due to the disinfectant (absorber) can be obtained.

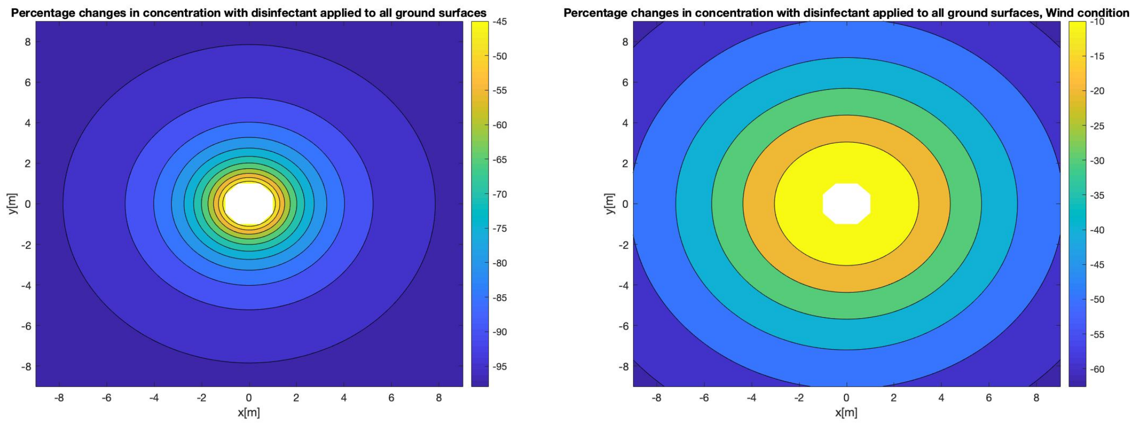

Figure 4: Percentage changes due to the disinfectant with no wind condition (left) and 3m/s south-west wind condition (right)

As shown in Figure 4, applying disinfectant on the ground surface during the duration of the concert such that the ground surface functions as an absorber have significant effect on reducing the virus concentration at head height level at the end of the concert. These changes range from -10 % to -95 %, depending on the wind condition and the distance from the source of the point of release of the virus.

1.4 (d) Vertical distribution of the concentration of the virus from ground level to the head height of a performer

The vertical distribution of the concentration of the virus from ground level to the head height of the performer, at a position directly in front of the centre of the stage, can be obtained by applying equations 2, 4, 5, and 6 on x=0m, y=15m, and between z=-1.8m (ground surface) and z=3m (head of performer). This will obtain distribution as shown below.

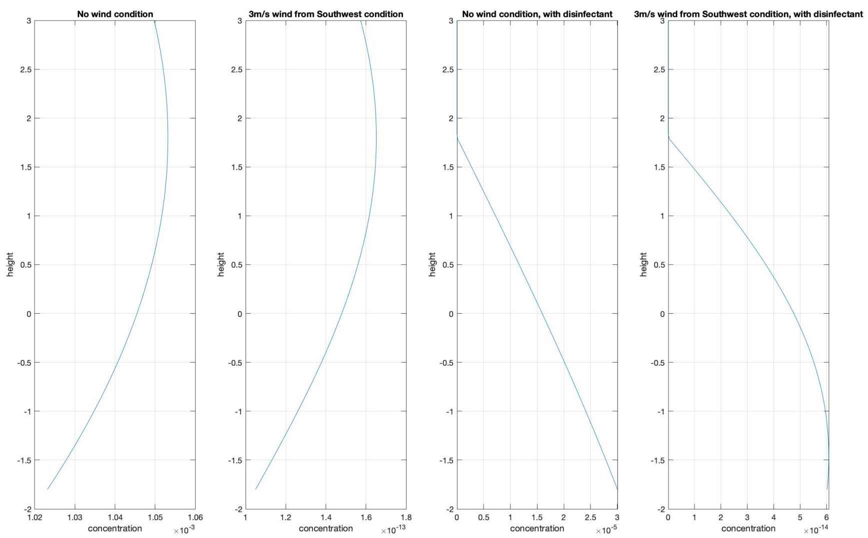

Figure 5: Vertical distribution of concentration of virus directly in front of the centre of the stage

The distribution in Figure 5 shows that when no disinfectant is applied at the ground, at the head height level of the performer (z=3m), the virus concentration is approximately 1.05 x 10^{-3} for no wind condition (diffusion only) and 1.6 x 10^{-13} for 3m/s south-west wind condition (diffusion and advection).

The concentration for no wind condition (diffusion only) is also significantly higher than the concentration for 3 m/s South-west wind condition (diffusion and advection). While on the other hand, if disinfectant is applied on the ground surface such that it functions as an absorber of the virus, the concentration of the virus at the head height level of the performer is 0. This is an effect of the Dirichlet boundary conditions, where for large times, the peak concentration shifts from the point of release (z=0) the boundary (z=-1.8m).

1.5 (e) Effects of raising viewing platforms within the public area to a height of 2m

In raising each of the viewing platforms within the public area to a height of 2m above the ground, the point of release of the virus is raised to 3.8m, and assuming everyone is of the same height (1.8m), the head height level of concertgoers is at z=3.8m. The viewing platform is also assumed to be permeable, such that it is not a boundary and acts as neither absorber or reflector. As a result, only the z level of the point of release changes.

To get the effects of raising the viewing platforms, 4 scenarios at the end of the concert are considered. These are: 1) No disinfectant, No wind. 2) No disinfectant, 3m/s wind from South-west. 3) Disinfectant applied on ground surface, no wind. 4) Disinfectant applied on ground surface, 3m/s wind from South-west.

The results are compared as a percentage proportion of the virus concentration when the viewing platforms are not elevated.

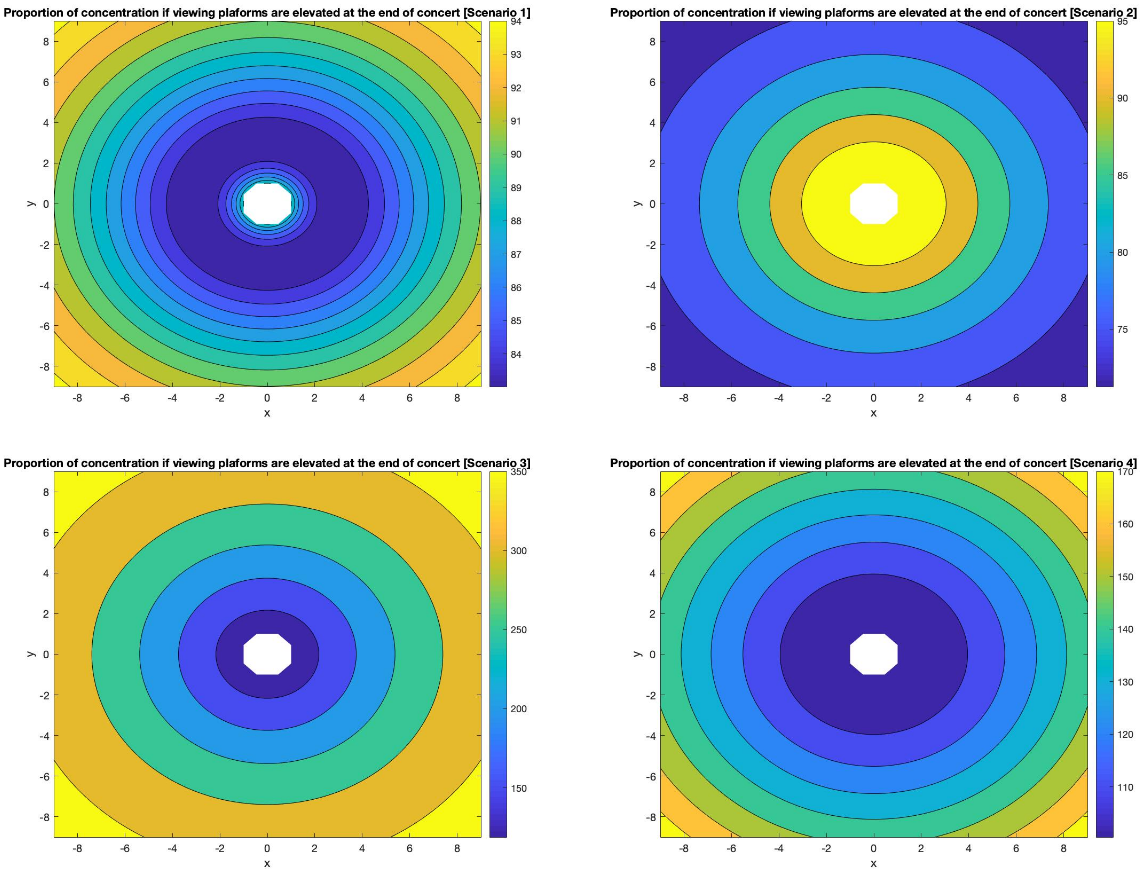

Figure 6: Virus concentration proportion when viewing platforms are elevated

As observed from the contour plot in Figure 6, when the viewing platforms are raised and there is no disinfectant applied on the ground surface (z=0) and the ground surface acts as a reflector (in scenarios 1 and 2), there is slight decrease in the concentration of virus at the end of the concert. The decrease in virus concentration within the concert ground of platforms 1 to 25 ranges from 6% to 17% in scenario 1 and 5% to 30% in scenario 2. This reduces the virus concentration to between 83% and 94% in scenario

1 (as proportion of not elevating the viewing platforms) and 70% and 95% in scenario 2.

However, when disinfectant is applied on the ground surface (z=0) such that the ground surface acts as an absorber of the virus, raising the viewing platform will increases the distance between the head height and the absorber ground surface, as a result, at the end of the concert, the virus concentration increases significantly, up to 350% of unelevated platform concentraion levels in scenario 3, and 170% in scenario 4.

Furthermore, elevating the platform by 2m will also decrease the difference between head-height level of the performers and the concertgoers, if the stage level is not raised. This increases the risk towards the performers.

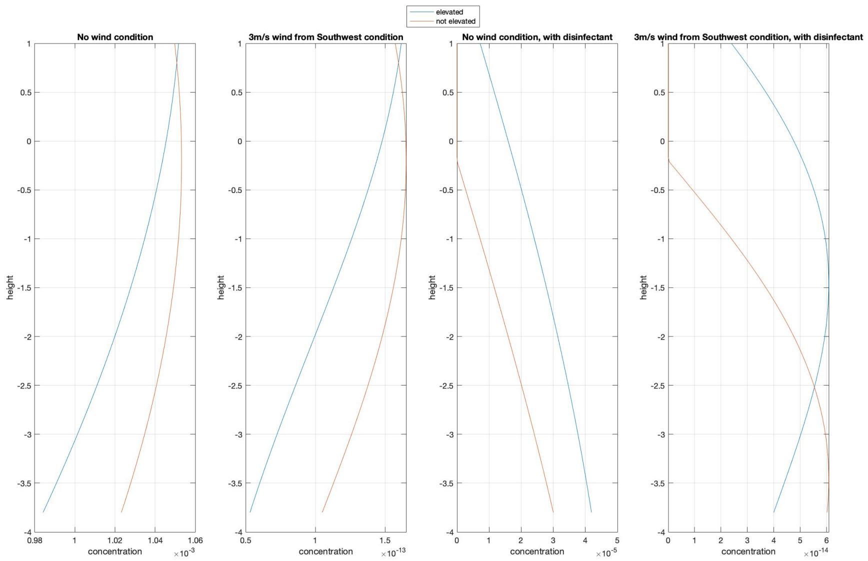

Figure 7: Vertical distribution of concentration of virus directly in front of the centre of the stage

As observed in Figure 7, the concentration of virus at head height of the performer (z=1m) increases across different scenarios when the viewing platforms are elevated.

2 Indoor transmission of COVID-19

2.1 (a) Maximum room occupants based on opening depth d

In a classroom with well-mixed air, the quanta per unit volume (concentration) c of SARS-CoV-2 due to emission from one infected person is given by

$$\frac{dc}{dt} = \frac{G}{V} - \frac{Qc}{V} \tag{9}$$

Where V is the volume of the classroom, G is the quanta emission rate per infected person, and Q is the volume flux of outdoor air entering the classroom. In this indoor classroom scenario, V is 200 m^3, G is 1 hr^{-1} (based on breathing without speaking activity). The volume flux of outdoor air entering the classroom is given by

$$Q = \frac{k}{3} w\sqrt{bd^3} \tag{10}$$

Where k is coefficient of mixing, w is width of opening, b is buoyancy due to temperature difference, and d is depth of opening. In this scenario, k is taken as 0.5 for vertical plane, width is 6 m, d varies, and b is governed by

$$\frac{db}{dt} = \frac{F}{V} - \frac{Qc}{V} \tag{11}$$

Where F is buoyancy flux. In air, 100 W is equivalent to a buoyancy flux of F = 0.0028 $m^4 s^{-3}$. F is assumed to be a function of N, number of occupants in the indoor environment, such that

$$F = 0.028 + 0.0028N \tag{12}$$

As a result, equation (11) can be simplified to

$$\frac{db}{dt} = \frac{0.028 + 0.0028N}{V} - \frac{Qc}{V} \tag{13}$$

Probability of someone in the classroom becoming infected by the virus, at a given time t, p(t) is also determined by the concentration c, and is given by

$$\frac{dp}{dt} = r(N-1)(1-p)c \tag{14}$$

Where r = 0.0002 $m^3 s^{-1}$ is the volume flux of respiration per person.

Applying Ordinary Differential Equations on equations (9), (13), and (14), the optimum depth of opening d to maximise number of occupants N, while keeping temperature above 17°C and probability of someone being infected below 0.01, can be obtained.

This is done by varying d from 0.10m by a step of 0.01m, obtaining the maximum number of occupants that can be obtained, and the corresponding temperature of the room. After a number of iterations, the optimum d is obtained as **0.47m**, where **14 people** can occupy the room, and the temperature is kept at 290K (17 °C).

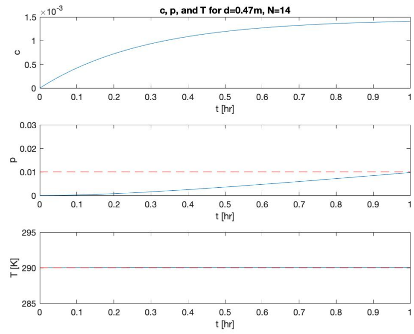

Figure 8: Concentration c, probability p, and temperature T for optimum depth of opening d=0.47m

2.2 (b) Maximum room occupants for consecutive classes

For consecutive classes with 30 minutes gap in between, periodic boundary conditions c(0) = c(1.5 hours), b(0) = b(1.5 hours) are applied. Thus, iterating over varied opening depth d, the optimum opening depth of **d=0.29m**, which will allow maximum occupancy of **8 people** is obtained.

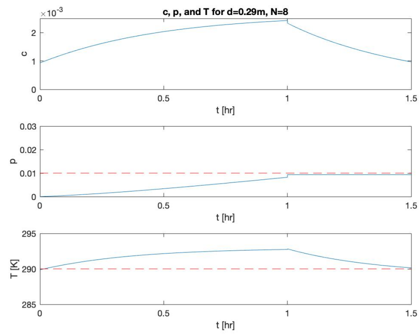

Figure 9: Concentration c, probability p, and temperature T for optimum depth of opening d=0.29m

2.3 (c) Addition of a low-level opening in the classroom

When the room has one opening as simulated in the scenarios in (a) and (b), the room is treated as a box with only one opening at high level. The formation of a warm upper layer is not possible because cool air enters at high level and would mix and dilute the upper layer. This will allow the air inside the box to be 'well-mixed' and of uniform temperature/buoyancy (Linden 1999). On the other hand, if another

low-level opening in the classroom is added, the air flow will be driven in at the low level opening and driven out at the high level opening. This is caused by the difference of pressure. Inside the room, there is also a height h where internal pressure is equal to external pressure. This is called the neutral pressure level. Above this level, the fluid will be drawn out of the room and below this level, the fluid will be driven into the room (Linden 1999).

This can be illustrated in Figure 8 below.

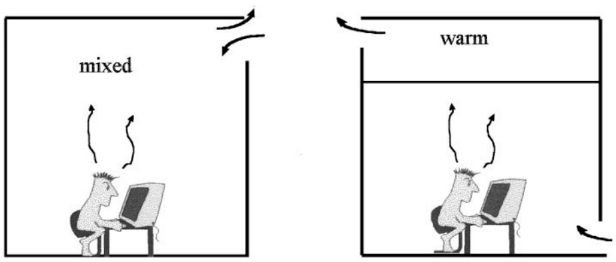

Figure 10: Illustration of well-mixed air in a box with one opening (Linden 1999)

Adding a low-level opening will create a flow of air in the room as mentioned and illustrated above. This will create a stably stratified interior and a large temperature differences in the room. This is a result of hot air rising to the top level of the room.

However, adding a low level opening will also allows displacement ventilation, which is more efficient than the mixing ventilation in a one-opening room. This will minimise concentration of SARS-CoV-2 virus in the air in the room, as when it is released by the infected person, it moves upwards due to the pressure gradient and ultimately leaves the room from the high-level opening. This ventilation method, referred as engineering controls, is also considered by the US Centres of Disease Control (CDC) to be the second most effective way to reduce infection by a pathogen, by separating the people and the pathogen (Morawska et al. 2020).

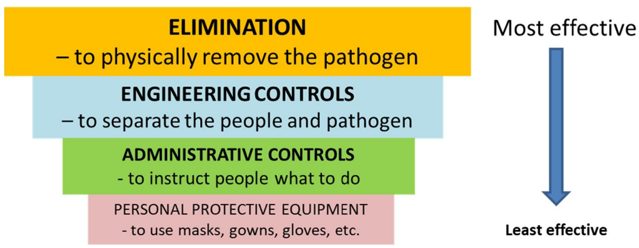

Figure 11: US Centres of Disease Control (CDC) recommendation to reduce potential airborne transimission of pathogen

In conclusion, adding a low-level opening can minimise the airborne transmission of SARS-CoV-2 due to the creation of displacement ventilation. However, it will create a temperature gradient in the room as hot air rises to the top level of the space. This will lead to the room being in a lower temperature, and more energy needs to be used for heating.

References

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APPPENDIX MATLAB Codes for Question 1

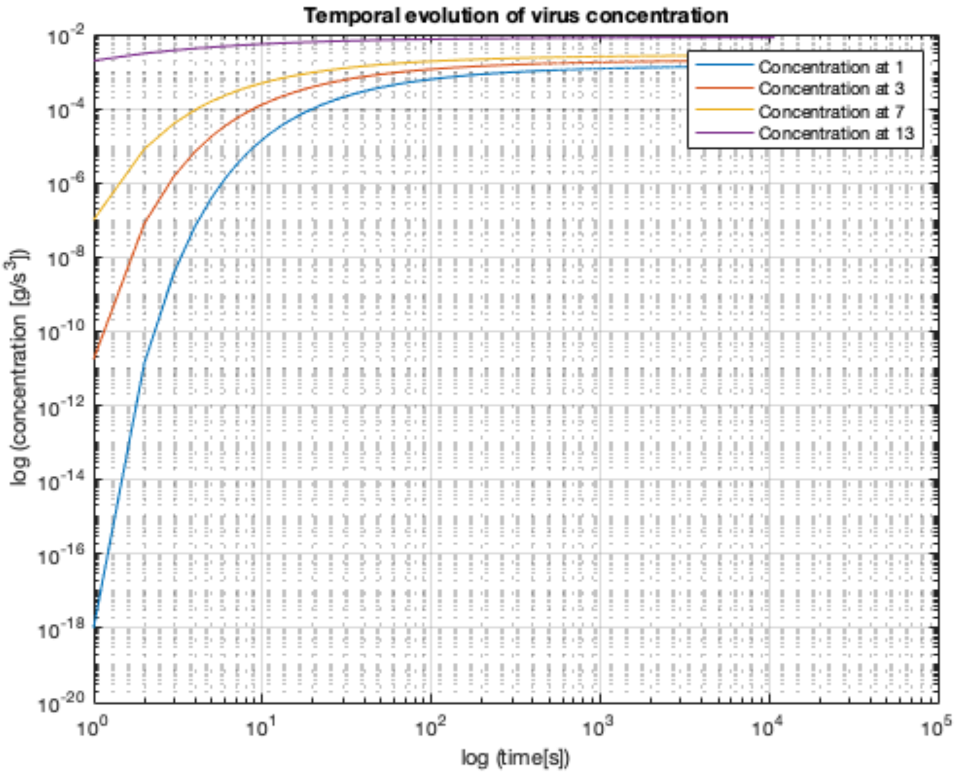
Table of Contents


```
clear;
clc;
close all;

% 1. Outdoor Transmission of COVID-19
```

Part (a)

Assume no change in z

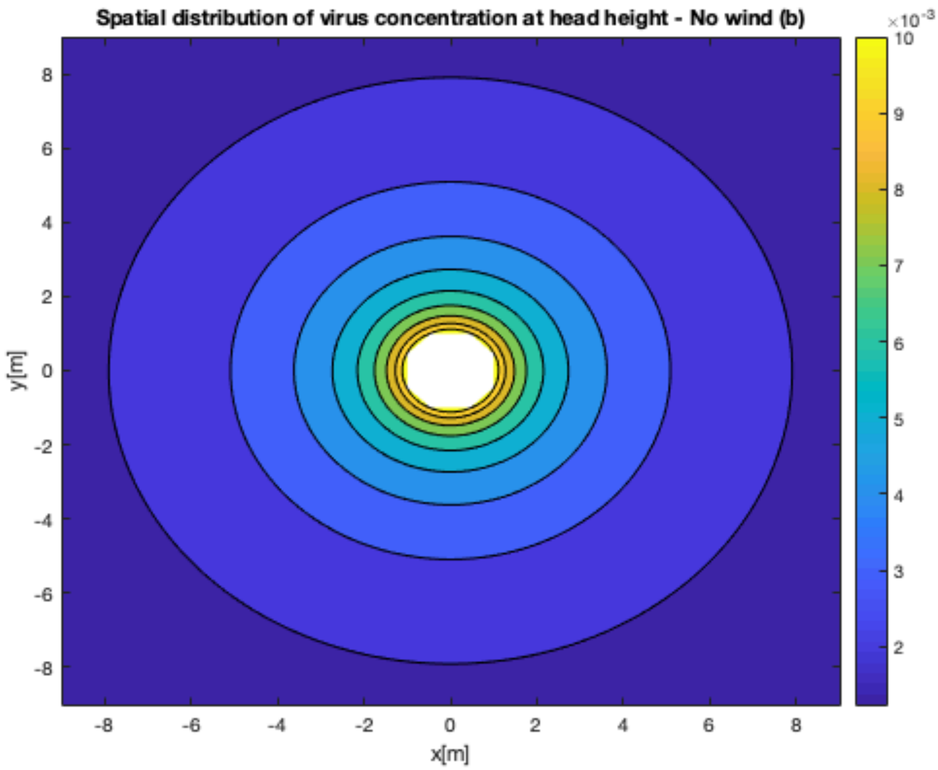
```
D= 1; % m^2 s^-1, assumption
t_a=linspace(0,10800,10800); % time for 3 hours concert
M=98/3600*4; % M for 4 people, singing loudly

% Coordinates of platforms 1, 3, 7, 13
x_a1=-8;y_a1=8;
x_a3=0;y_a3=8;
x_a7=-4;y_a7=4;
x_a13=1;y_a13=1;

% Height of people (assumption)
h=1.8;

% Concentration at head height level at platforms 1, 3, 7, 13
C1=function1(x_a1, y_a1, 0 ,M , D, t_a,h);
C3=function1(x_a3, y_a3, 0 ,M , D, t_a,h);
C7=function1(x_a7, y_a7, 0 ,M , D, t_a,h);
C13=function1(x_a13, y_a13, 0 ,M , D, t_a,h);

figure;
loglog(t_a, C1, t_a, C3, t_a, C7, t_a, C13)
legend('Concentration at 1','Concentration at 3','Concentration at
 7','Concentration at 13');
grid on
xlabel('log (time[s])');
ylabel('log (concentration [g/s^3])');
title('Temporal evolution of virus concentration');
```

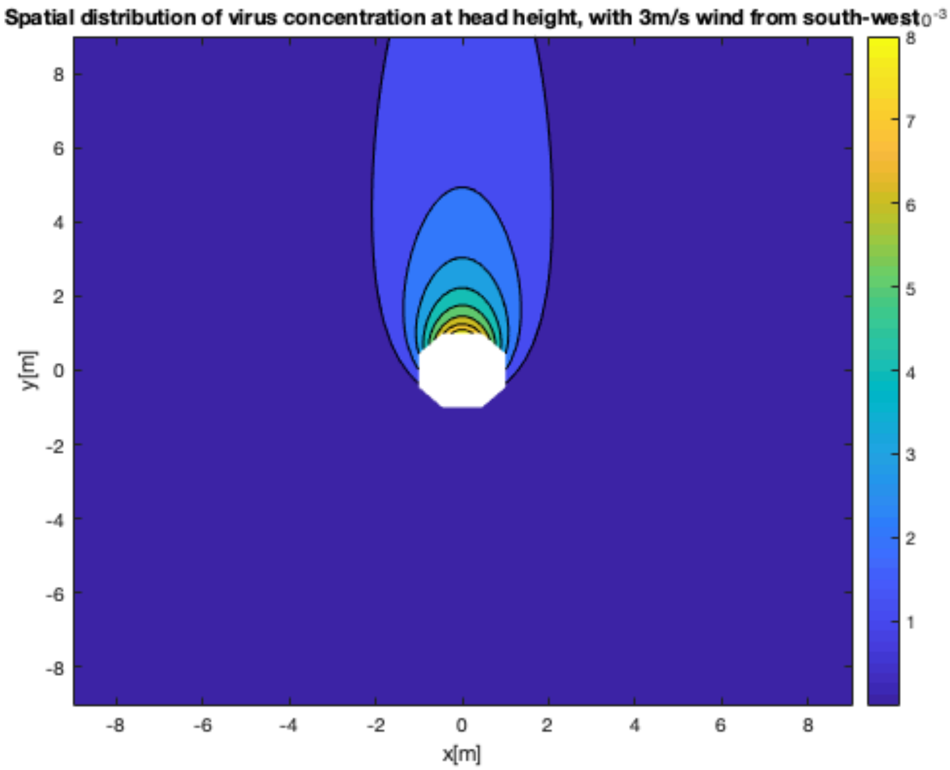


Part (b)

```
%Initialise x and y coordinates of the concert space
x_b = linspace (-9, 9);
y_b = linspace (-9, 9);
z_b=0; % z refers to the z difference of all the concertgoers, as the
 concertgoers are assumed to be of the same height, z=0
t_b=10800; % end of concert

fxy=zeros(length(x_b), length (y_b));
for j=1:length(x_b)
    for k=1:length(y_b)
        fxy(j,k)=function1(x_b(j),y_b(k),0, M, D, t_b,h);
    end
end

figure;
contourf(x_b, y_b, fxy)
xlabel('x[m]')
ylabel('y[m]')
zlabel('concentration')
title('Spatial distribution of virus concentration at head height - No
 wind (b)')
colorbar
```

```
U=3;
fxy2=zeros(length(x_b), length (y_b));
for j=1:length(x_b)
    for k=1:length(y_b)
        fxy2(j,k)=function2(x_b(j),y_b(k),0, M, D, t_b, U, h);
    end
end


figure;


contourf(x_b, y_b, fxy2)
xlabel('x[m]')
ylabel('y[m]')
zlabel('concentration')
title('Spatial distribution of virus concentration at head height,
 with 3m/s wind from south-west')


colorbar
```



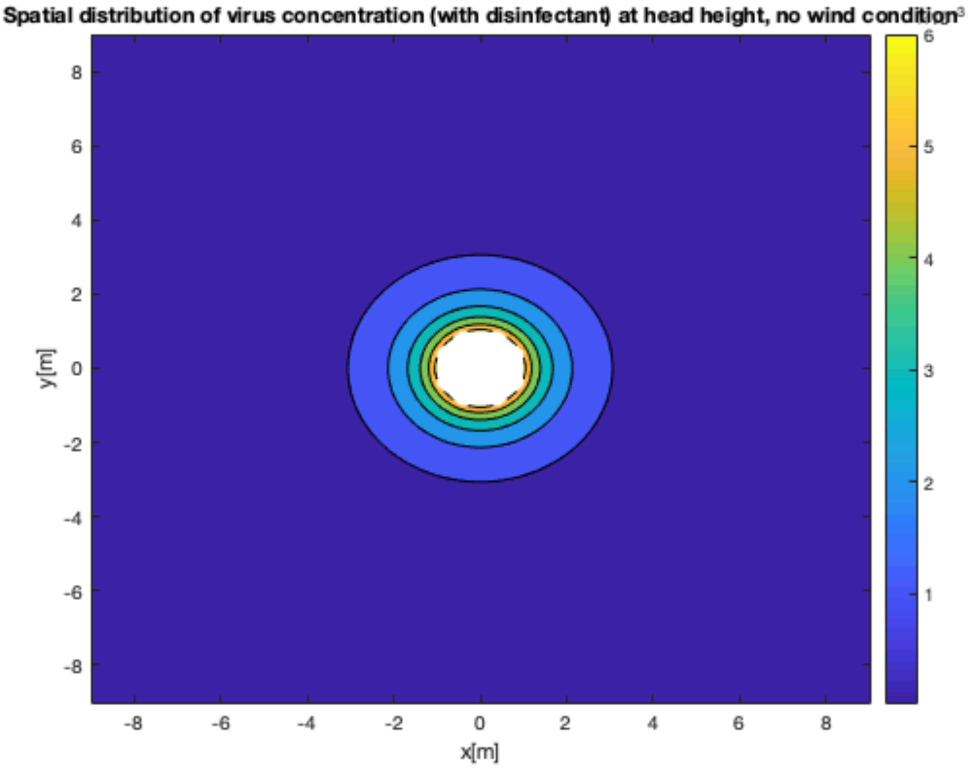


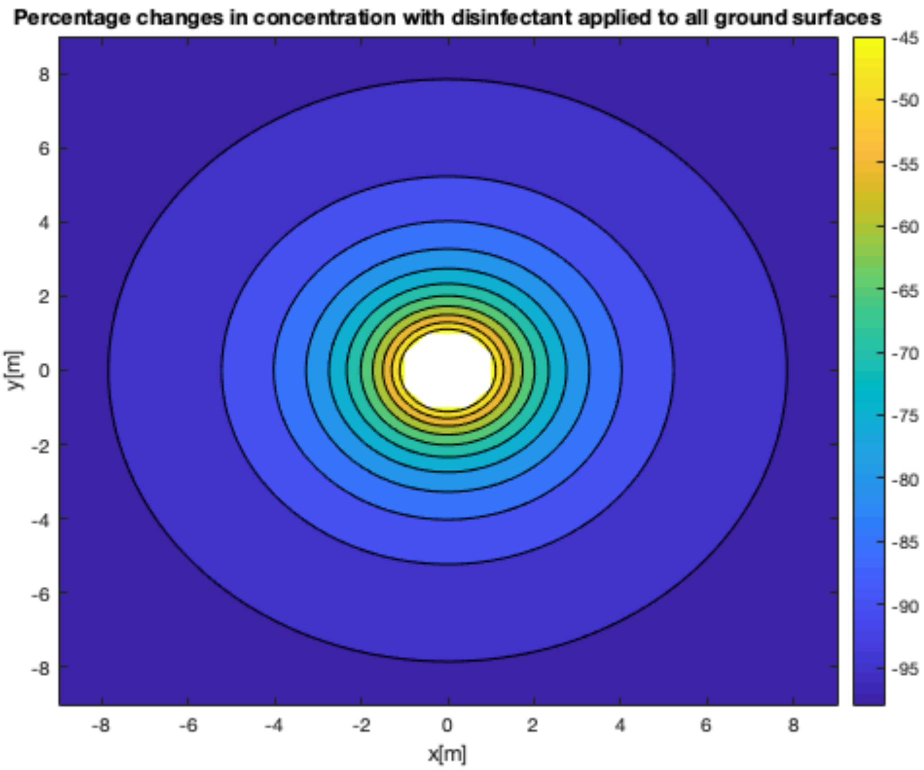
Part (c)

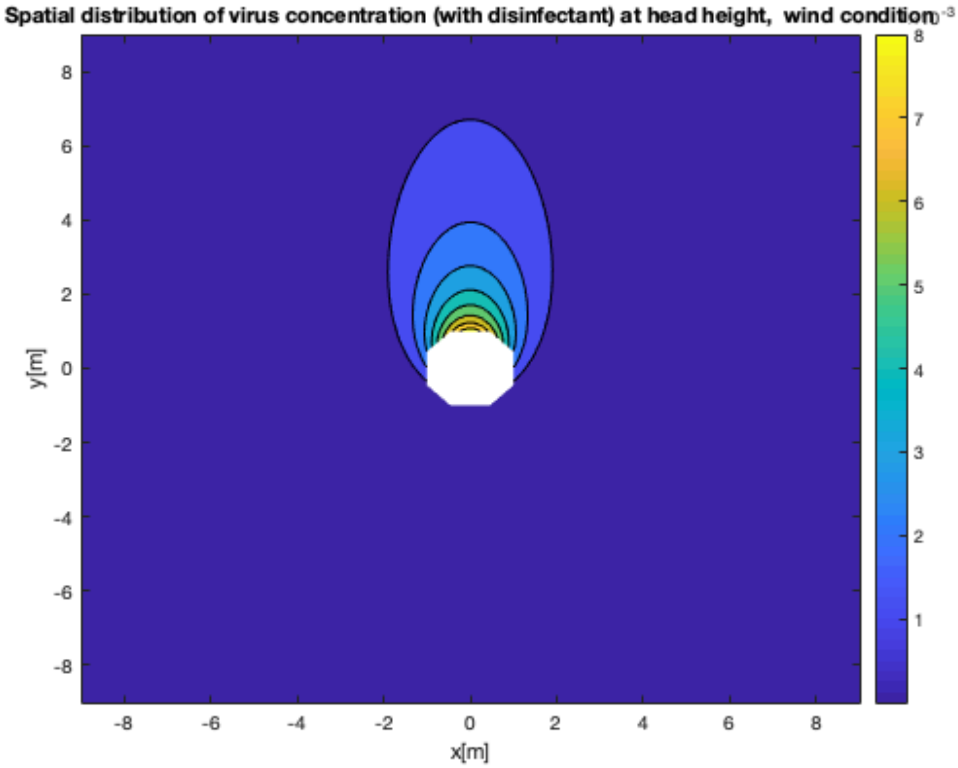
1 - No wind condition

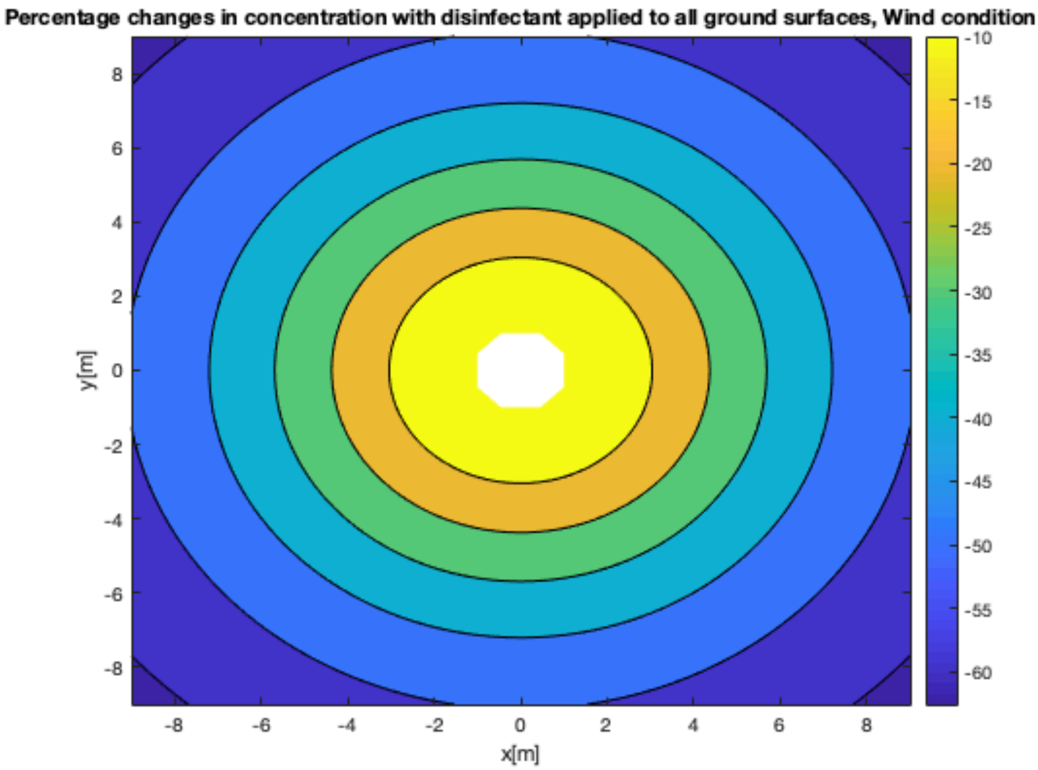
```
x_c = linspace (-9, 9);
y_c = linspace (-9, 9);
z_c=0;
t_c=10800;

fxy_c=zeros(length(x_c), length (y_c));
changes_c=zeros(length(x_c), length (y_c));
for j=1:length(x_c)
    for k=1:length(y_c)
        fxy_c(j,k)=function3(x_b(j),y_b(k),z_c, M, D, t_c,  1.8);
        changes_c(j,k)=((fxy_c(j,k)-fxy(j,k))/fxy(j,k))*100; % Changes
 represent the percentage changes between absorber and reflector
 ground surface conditions
    end
end

figure;
contourf(x_c, y_c, fxy_c)
xlabel('x[m]')
ylabel('y[m]')
zlabel('Concentration')
colorbar
```

```
title('Spatial distribution of virus concentration (with disinfectant)
 at head height, no wind condition')


figure;

contourf(x_c, y_c, changes_c)
xlabel('x[m]')
ylabel('y[m]')
zlabel('changes %')
title('Percentage changes in concentration with disinfectant applied
 to all ground surfaces')
colorbar

% Wind condition

fxy_c2=zeros(length(x_c), length (y_c));
changes_c2=zeros(length(x_c), length (y_c));
for j=1:length(x_c)
    for k=1:length(y_c)
        fxy_c2(j,k)=function4(x_b(j),y_b(k),z_c, M, D, t_b, U, 1.8);
        changes_c2(j,k)=((fxy_c2(j,k)-fxy2(j,k))/fxy2(j,k))*100;
    end
end

figure;


contourf(x_c, y_c, fxy_c2)
xlabel('x[m]')
ylabel('y[m]')
zlabel('Concentration')
colorbar
title('Spatial distribution of virus concentration (with disinfectant)
 at head height,  wind condition')

figure;

contourf(x_c, y_c, changes_c2)
xlabel('x[m]')
ylabel('y[m]')
zlabel('changes %')
title('Percentage changes in concentration with disinfectant applied
 to all ground surfaces, Wind condition')
colorbar
```


Spatial distribution of virus concentration (with disinfectant) at head height, no wind condition
y[m]
x[m]
8
6
4
2
0
-2
-4
-6
-8
6
5
4
3
2
1


Percentage changes in concentration with disinfectant applied to all ground surfaces
y[m]
x[m]
8
6
4
2
0
-2
-4
-6
-8
-45
-50
-55
-60
-65
-70
-75
-80
-85
-90
-95

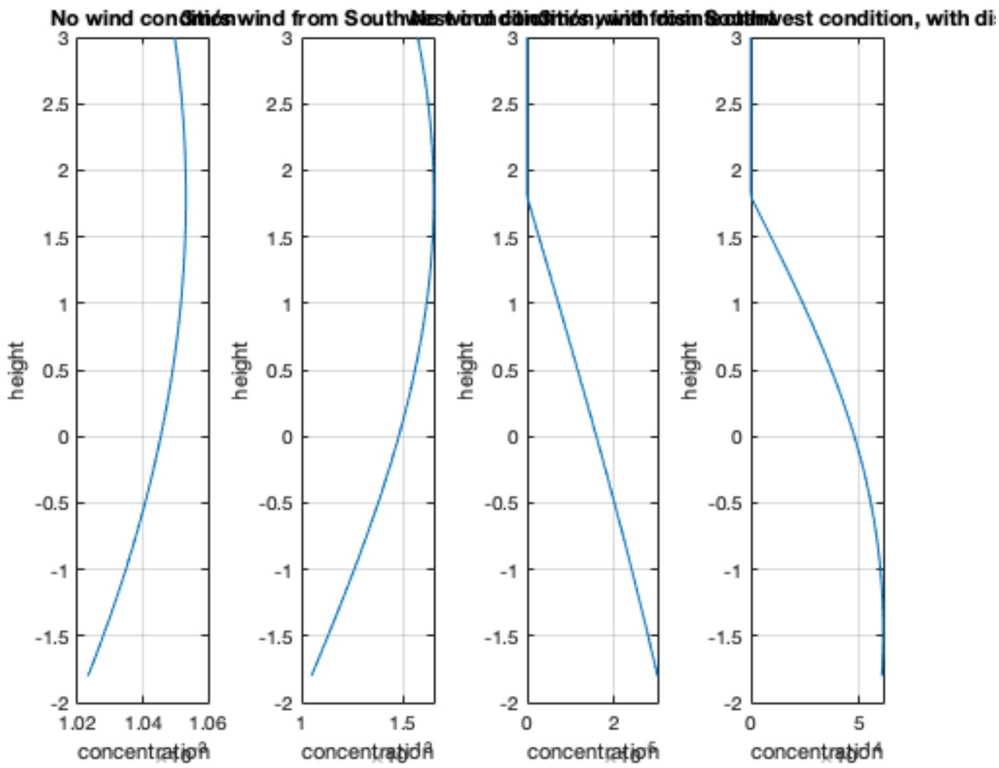

Spatial distribution of virus concentration (with disinfectant) at head height, wind condition
10^{-3}
y[m]
x[m]


Percentage changes in concentration with disinfectant applied to all ground surfaces, Wind condition
y[m]
x[m]

Part (d)

```
%(i) No wind
z_d=linspace(-1.8,3);
x_d=0;
y_d=15;
t_d=10800;

for i=1:length(z_d)
    fxy3(i)=function1(x_d, y_d, z_d(i), M, D, t_d,h);
end

% (ii) Wind, 3m/s from South West
for i=1:length(z_d)
    fxy4(i)=function2(x_d, y_d, z_d(i), M, D, t_d, U,h);
end

for i=1:length(z_d)
    fxy5(i)=function3(x_d, y_d, z_d(i), M, D, t_d,h);
end

for i=1:length(fxy5)
    if fxy5(i)<0
        fxy5(i)=0;
    end
end

for i=1:length(z_d)
    fxy6(i)=function4(x_d, y_d, z_d(i), M, D, t_d, U,h);
end

for i=1:length(fxy6)
    if fxy6(i)<0
        fxy6(i)=0;
    end
end

figure

subplot(1,4,1)
plot(fxy3, z_d);
xlabel('concentration');
ylabel('height');
grid on
title('No wind condition')

subplot(1,4,2)
plot(fxy4, z_d);
xlabel('concentration');
ylabel('height');
grid on
title('3m/s wind from Southwest condition')
```

```
subplot(1,4,3)
plot(fxy5, z_d);
xlabel('concentration');
ylabel('height');
grid on
title('No wind condition, with disinfectant')

subplot(1,4,4)
plot(fxy6, z_d);
xlabel('concentration');
ylabel('height');
grid on
title('3m/s wind from Southwest condition, with disinfectant')
```



Part (e)

```
% Scenario 1, no wind condition, with reflector at z=0m ground
 surface, at
% the end of concert

% Height of people + elevated platform (assumption)
h_e=3.8;

fxye1=zeros(length(x_b), length (y_b));
for j=1:length(x_b)
```

```
    for k=1:length(y_b)
        fxye1(j,k)=function1(x_b(j),y_b(k),0, M, D, t_b,h_e);
    end
end

diff_e1=fxye1./fxy.*100;

figure;
contourf(x_b, y_b, diff_e1)

colorbar
xlabel('x');
ylabel('y');
title('Proportion of concentration if viewing plaforms are elevated at
 the end of concert [Scenario 1]');


% Scenario 2; 3m/s South-west wind, with reflector at z=0m ground
 surface

fxye2=zeros(length(x_b), length (y_b));
for j=1:length(x_b)
    for k=1:length(y_b)
        fxye2(j,k)=function2(x_b(j),y_b(k),0, M, D, t_b,U, h_e);
    end
end

% Proportion of concentration of virus at at the end of concert as
 compared to not elevated platforms
diff_e2=fxye2./fxy2.*100;

figure;
contourf(x_b, y_b, diff_e2)

colorbar
xlabel('x');
ylabel('y');
title('Proportion of concentration if viewing plaforms are elevated at
 the end of concert [Scenario 2]');


% Scenario 3; at the end of concert, with absorber
fxye3=zeros(length(x_b), length (y_b));
for j=1:length(x_b)
    for k=1:length(y_b)
        fxye3(j,k)=function3(x_b(j),y_b(k),0, M, D, t_b,h_e);
    end
end

% Proportion of concentration of virus at at the end of concert as
 compared to not elevated platforms
diff_e3=fxye3./fxy_c.*100;

figure;
```

```
contourf(x_b, y_b, diff_e3)

colorbar
xlabel('x');
ylabel('y');
title('Proportion of concentration if viewing plaforms are elevated at
 the end of concert [Scenario 3]');

% Scenario 4; at the end of concert, with absorber, southwest wind
% condition

fxye4=zeros(length(x_b), length (y_b));
for j=1:length(x_b)
    for k=1:length(y_b)
        fxye4(j,k)=function4(x_b(j),y_b(k),0, M, D, t_b,U, h_e);
    end
end

% Proportion of concentration of virus at at the end of concert as
 compared to not elevated platforms
diff_e4=fxye4./fxy_c2.*100;

figure;
contourf(x_b, y_b, diff_e4)

colorbar
xlabel('x');
ylabel('y');
title('Proportion of concentration if viewing plaforms are elevated at
 the end of concert [Scenario 4]');



z_e=linspace(-3.8,1);

for i=1:length(z_e)
    fxy3e(i)=function1(x_d, y_d, z_e(i), M, D, t_d,h);
end

for i=1:length(z_e)
    fxy4e(i)=function2(x_d, y_d, z_e(i), M, D, t_d, U,h);
end

for i=1:length(z_e)
    fxy5e(i)=function3(x_d, y_d, z_e(i), M, D, t_d,h);
end

for i=1:length(fxy5e)
    if fxy5e(i)<0
        fxy5e(i)=0;
    end
end

for i=1:length(z_e)
```

```
    fxy6e(i)=function4(x_d, y_d, z_e(i), M, D, t_d, U,h);
end

for i=1:length(fxy6e)
    if fxy6e(i)<0
        fxy6e(i)=0;
    end
end

subplot(1,4,1)
plot(fxy3e, z_e, fxy3,z_e);
xlabel('concentration');
ylabel('height');
grid on
title('No wind condition')
legend('elevated', 'not elevated')

subplot(1,4,2)
plot(fxy4e, z_e, fxy4, z_e);
xlabel('concentration');
ylabel('height');
grid on
title('3m/s wind from Southwest condition')
legend('elevated', 'not elevated')


subplot(1,4,3)
plot(fxy5e, z_e, fxy5, z_e);
xlabel('concentration');
ylabel('height');
grid on
title('No wind condition, with disinfectant')
legend('elevated', 'not elevated')

subplot(1,4,4)
plot(fxy6e, z_e, fxy6, z_e);
xlabel('concentration');
ylabel('height');
grid on
title('3m/s wind from Southwest condition, with disinfectant')
legend('elevated', 'not elevated')
```

Functions

Virus concentration at a given time t with no wind.

```
function [C] = function1(x, y, z, M, D, t, h)
r= sqrt(x.^2+y.^2+z.^2);
if r<1
    r=NaN;
end
r_2=sqrt(x.^2+y.^2+(z-2*h).^2);
```

MATLAB Codes for Question 2

Table of Contents

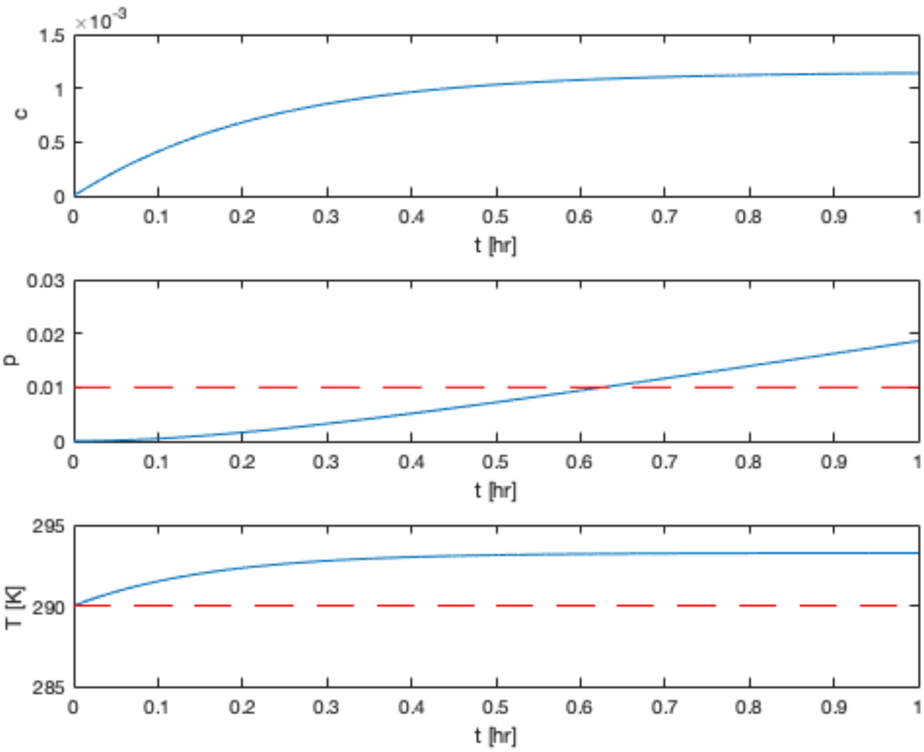

```
clear;
clc;
close all;
```

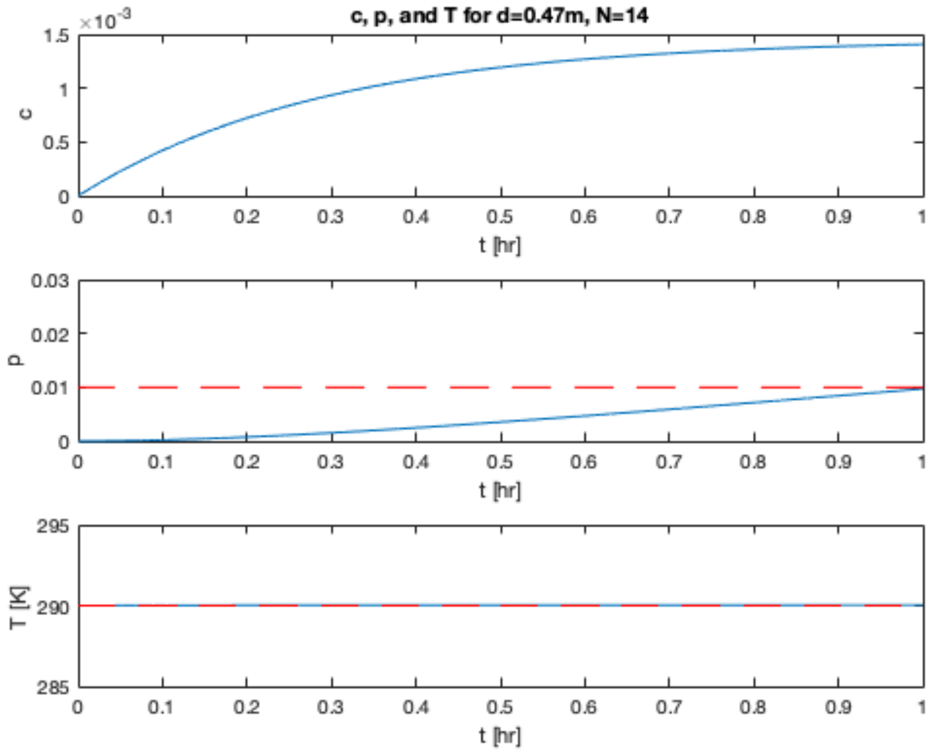
Question 2 (a)

```
k=0.5;
w=6;
V=200;
G=1/3600;

T0=280;
T1=290;
g=9.81;

r=0.0002;


N0=30;
d0=0.5;

b0=g*(T1-T0)/T0;
c0=0;
p0=0;

pmeters=[b0; c0; p0];
% [t, dxdt]=ode45(@f,t, INPUTS)
tspan=1:3600; %s

[t, x1]=ode45(@function1, tspan, pmeters,[], N0, V, k, w, d0, G,r);

Ti=((T0/g).*x1(:,1))+T0;


figure;
subplot(3,1,1)
plot(t/3600,x1(:,2))
xlabel('t [hr]')
ylabel('c')
xlim([0,1])
ylim([0,0.0015])
```

```
subplot(3,1,2)
plot(t/3600,x1(:,3), t/3600, 0.01*ones(1,length(t)), '--r');
xlabel('t [hr]')
ylabel('p')
xlim([0,1])
ylim([0,0.03])

subplot(3,1,3)
plot(t/3600,Ti, t/3600, 290*ones(1,length(t)), '--r')
xlabel('t [hr]')
ylabel('T [K]')
xlim([0,1])
ylim([285,295])

d=0.1:0.01:1;

p=Inf;
C=1;
for i =d
    N=30;
    n=1;
    p(end)=Inf;

    while p(end)>0.01
        [t, x]=ode45(@function1, tspan, pmeters,[], N, V, k, w, i,
 G,r);
        p=x(:,3);
        N=N-1;
    end
    Ti=((T0/g).*x(end,1))+T0;



    if Ti<290
        break
    end
    data(C, 1)=i;
    data(C, 2)=N+1;
    data(C, 3)= Ti;
    C=C+1;
end

fprintf('(a) d= %g, N= %g, T= %g. \n', data(end, 1), data(end, 2),
 data(end,3));

[t, x1_2]=ode45(@function1, tspan, pmeters,[], data(end, 2), V, k, w,
 data(end, 1), G, r);
Ti_2=((T0/g).*x1_2(:,1))+T0;

figure;
subplot(3,1,1)
plot(t/3600,x1_2(:,2))
xlabel('t [hr]')
ylabel('c')
```

```
xlim([0,1])
ylim([0,0.0015])
title('c, p, and T for d=0.47m, N=14')

subplot(3,1,2)
plot(t/3600,x1_2(:,3), t/3600, 0.01*ones(1,length(t)), '--r');
xlabel('t [hr]')
ylabel('p')
xlim([0,1])
ylim([0,0.03])

subplot(3,1,3)
plot(t/3600,Ti_2, t/3600, 290*ones(1,length(t)), '--r')
xlabel('t [hr]')
ylabel('T [K]')
xlim([0,1])
ylim([285,295])
```





2 (b)

```
c0=0.0002;
p0=0;
param=[b0;c0;p0];
for i=1:4

    [t1, xb1]=ode45(@function1, 1:3600, param, [], N0, V, k, w, d0,
 G,r);
    [t2, xb2]=ode45(@function1, 1:1800,
 [xb1(end,1),xb1(end,2),xb1(end,3)],[], 0, V, k, w, d0, 0,0);

    param=[xb2(end,1),xb2(end,2),p0];
end
Tib1=((T0/g).*xb1(:,1))+T0;Tib2=((T0/g).*xb2(:,1))+T0;
Tib=cat(1,Tib1, Tib2);
xbb = cat(1,xb1,xb2);

tb=[1:5400];
figure;
subplot(3,1,1)
plot(tb/3600,xbb(:,2))
xlabel('t [hr]')
ylabel('c')
xlim([0,1.5])
```

```
ylim([0,0.0015])

subplot(3,1,2)
plot(tb/3600,xbb(:,3), tb/3600, 0.01*ones(1,length(tb)), '--r')
xlabel('t [hr]')
ylabel('p')
xlim([0,1.5])
ylim([0,0.03])

subplot(3,1,3)
plot(tb/3600,Tib, tb/3600, 290*ones(1,length(tb)), '--r')
xlabel('t [hr]')
ylabel('T[K]')
xlim([0,1.5])
ylim([285,295])


C=1;
for i =d
    N=30;
    n=1;
    p(end)=Inf;

    while p(end)>0.01

        param=[b0;c0;p0];
        for j=1:4
            [t1, xb1]=ode45(@function1, 1:3600, param, [], N, V, k, w,
 i, G,r);
            [t2, xb2]=ode45(@function1, 1:1800,
 [xb1(end,1),xb1(end,2),xb1(end,3)],[], 0, V, k, w, i, 0,0);
            param=[xb2(end,1),xb2(end,2),p0];
        end


        p=xb2(:,3);
        N=N-1;
    end
    Ti=((T0/g).*xb2(end,1))+T0;


    if Ti<290
        break
    end
    data2(C, 1)=i;
    data2(C, 2)=N+1;
    data2(C, 3)= Ti;
    C=C+1;
end

fprintf('(b) d= %g, N= %g, T= %g. \n', data2(end, 1), data2(end, 2),
 data2(end,3));
```

```
[t1, xb21]=ode45(@function1, 1:3600, param, [], 7, V, k, w, 0.29, G,
 r);
[t2, xb22]=ode45(@function1, 1:1800,
 [xb1(end,1),xb1(end,2),xb1(end,3)],[], 0, V, k, w, 0.29, 0,0);
Ti_21=((T0/g).*xb21(:,1))+T0;
Ti_22=((T0/g).*xb22(:,1))+T0;

xb2cat=cat(1,xb21, xb22);
Ti_cat=cat(1,Ti_21, Ti_22);

figure;
subplot(3,1,1)
plot(tb/3600,xb2cat(:,2))
xlabel('t [hr]')
ylabel('c')
xlim([0,1.5])
ylim([0,0.0025])
title('c, p, and T for d=0.29m, N=8')

subplot(3,1,2)
plot(tb/3600,xb2cat(:,3), tb/3600, 0.01*ones(1,length(tb)), '--r');
xlabel('t [hr]')
ylabel('p')
xlim([0,1.5])
ylim([0,0.03])

subplot(3,1,3)
plot(tb/3600,Ti_cat, tb/3600, 290*ones(1,length(tb)), '--r')
xlabel('t [hr]')
ylabel('T [K]')
xlim([0,1.5])
ylim([285,295])
```

Functions

```
function x= function1(t, pmeters, N, V, k, w, d, G,r )
b = pmeters(1); c=pmeters(2); p=pmeters(3);

dbdt=((0.0028*N +0.028)/V)-(((k/3)*w*sqrt(b*d^3))/V)*b;
dcdt=(G/V)-(((k/3)*w*sqrt(b*d^3))/V)*c;
dpdt=r*(N-1)*(1-p)*c;

x=[dbdt;dcdt;dpdt];
end
```

(a) d= 0.47, N= 14, T= 290.038.

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