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CFD BASED AIRFLOW MODELLING TO INVESTIGATE THE EFFECTIVENESS OF CONTROL METHODS INTENDED TO PREVENT THE TRANSMISSION OF AIRBORNE ORGANISMS

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ABSTRACT

The airborne transmission of disease is a constant threat and while diseases such as Tuberculosis were considered all but extinct in the western world, the resurgence of it demonstrates that the spread of these diseases has to be taken very seriously.

This paper describes the method of application of Computational Fluid Dynamics (CFD), more appropriately called Airflow Modelling for the Building Services Industry, to the airflow and heat transfer in a Hospital Isolation Room Application. In particular it addresses how it can determine the ability of the ventilation system to limit the time during which carers, or other people present in the room, may be at risk to the airborne organisms constantly being produced by a patient coughing, sneezing or simply talking.

Research has shown that ventilation rate is no guarantee of control of these airborne organisms. Another means of minimising the risk from airborne bacteria is to apply ultraviolet germicidal irradiation (UVGI). UVGI holds promise of greatly lowering the concentration of airborne bacteria and thus controlling the spread of airborne infection among occupants.

This paper describes the techniques developed to allow the airflow simulation to be extended to simulate the motion of the droplets carrying the bacteria, their path through the room and indeed any exposure they may have to UVGI. The work will be highlighted by a series of case studies demonstrating the effect of change in the ventilation design and the effect of UVGI on the probability of survival of the bacteria.

KEYWORDS

Airflow, Modelling, CFD, Particles, Droplets, UVGI, Bacteria

INTRODUCTION

Airflow modelling in the form of Computational Fluid Dynamics has now been established for some time as another method of analysing the ventilation performance in the built environment. Based on the iterative solution of the fundamental conservation equations in the form of the Navier-Stokes equation, Airflow Modelling provides the ability to predict such parameters as the pressure, velocity and temperature at often hundreds of thousands of points in space. As experimental facilities for full and part scale modelling become fewer and further between, and computers and software become faster and more powerful, more and more designs are taking advantage of the progress and using airflow modelling to evaluate the likely success of the proposed design. This is not only of benefit in the design of conventional occupied environments where there can be capital and running cost savings by identifying improved designs (not to mention the increase in productivity), but has been shown to be of critical importance in design for contamination control. In many contamination control applications, the particles are of the sub-micron level and at this size, there is little slip relative to the air in which they are situated. As a result, the particles can be considered as completely airborne and treated as if they are gaseous.

The resurgence of Tuberculosis (TB) an Multi-Drug-Resistant forms (MDR-TB) represents an application where the assumptions of this gaseous modelling approach are insufficient for a true analysis of the ventilation performance. Patients in hospital isolation rooms constantly produce transmissible airborne organisms by coughing, sneezing or talking, which, if not under control, results in spreading airborne infection. TB infection, for example, occurs after inhalation of a sufficient number of tubercle bacilli expelled during a cough by a patient (see Federal Register, 1993). The contagion depends on the rate at which bacilli are discharged, i.e., the number of the bacilli released from the infectious source. It also depends on the virulence of the bacilli as well as external factors, such as the ventilation flow rate. In order to prevent the transmission of airborne infection, isolation rooms are usually equipped with high efficiency ventilation systems operating at high supply flow rate to remove the airborne bacteria from the rooms. However, unexpected stagnant regions, or areas of poor mixing, mean that the ventilation rate is no guarantee of good control to the spreading of airborne infection. The risk from such an airborne spread is particularly important in places where people are ill since their immunity to infection is somewhat reduced. Hospitals are however not the only place where there is such a risk, others might include shelters for the homeless.

These bacteria when expelled normally reside in small colonies on droplets that are larger than the sub-micron scale (although as water evaporates they become progressively smaller), but, more importantly these bacteria can be killed by exposure to ultra violet germicidal irradiation, or UVGI for short. To understand the effect of such exposure it is essential to know the duration and intensity of exposure for each droplet. Knowing this the probability of the bacteria remaining alive can be assessed and thus an assessment of the risk can be made.

While traditionally protection has been provided by using by ventilation systems to continually change the air, and a knowledge of the dilution of the number of bacteria is sufficient to assess the risk, it is essential to predict the path and time for droplets spent in an ultra-violet beam. Now it should be recognised that a simple streamline for a droplet is insufficient to assess the ventilation performance of the room since each droplet will take a different path due to the way in which it interacts with the turbulence in the room. Further, bacteria may be projected by the cough or the sneeze to almost any point in the room, so it is necessary to take a statistical approach to the ventilation effectiveness super-imposed on the sound methodology of Airflow Modelling.

METHODOLOGY

The methodology is based on the assumption that the number of droplets is small in relation to the total airflow and so they do not affect the air movement. On this basis, the trajectory of the droplets can be calculated after solution of the airflow and assuming the turbulence is homogeneous, a Monte-Carlo approach used to statistically calculate the expected time for particles in the UV beam.

Droplet Trajectories

The methodology for predicting turbulent particle dispersion used in this study was originally laid out by Gosman, 1981and validated by Ormancey, 1984, Shuen, 1983, Chen, 1984. Experimental validation data was obtained from Snyder, 1971. Turbulence was incorporated into the Stochastic model via the k-ε turbulence model as given in Alani, 1998.

The particle trajectories are obtained by integrating the equation of motion in 3 co-ordinates. Assuming that body forces are negligible with the exception to drag and gravity, these equations can be expressed for the x direction as:

$$m_p \frac{du_p}{dt} = \frac{1}{2} C_D A_p \rho (u - u_p) \sqrt{(u-u_p)^2 + (v-v_p)^2 + (w-w_p)^2} + m_p g_x \qquad (1)$$

$$\frac{dx_p}{dt} = u_p \qquad (2)$$

and similarly for the y and z directions

Where

u, v, w:	instantaneous velocities of air in x, y and z directions
u_p, v_p, w_p:	particle velocity in x, y and z direction
x_p, y_p, z_p:	particle moving in x, y and z direction
g_x, g_y, g_z:	gravity in x, y and z direction
A_p	cross-section area of the particle
m_p	mass of the particle
ρ	density of the particle
C_D	drag coefficient
dt	time interval

The drag coefficient for a spherical particle, taken from Wallis [16], is:

$$C_D = \frac{24}{\mathrm{Re}}\left(1 + \frac{13}{16}\mathrm{Re}\right)^{0.5} \quad \text{for Re} \le 1000 \qquad (3)$$

and $C_D = 0.44$ for Re > 1000 (4)

The Reynolds number of the particle is based on the relative velocity between particle and air.

In laminar flow, particles released from a point source with the same weight would initially follow the air stream in the same path and then fall under the effect of gravity. Unlike in laminar flow, the random nature of turbulence indicates that the particles released from the same point source will be

randomly effected by turbulent eddies. As a result, they will be diffused away from the stream line at different fluctuating levels. In order to model the turbulent diffusion, the instantaneous fluid velocities in the 3 Cartesian directions, u, v and w are decomposed into the mean velocity component and the turbulent fluctuating component as:

$$u = \bar{u} + u', \; v = \bar{v} + v', \; w = \bar{w} + w'.$$

Where $\bar{u}$ and u' are the mean and fluctuating components in x-direction. The same applied for y-, z-directions. The stochastic approach prescribes the use of a random number generator algorithm which, in this case, is taken from Press, 1992 to model the fluctuating velocity. It is achieved through using a random sampling of a Gaussian distribution with a mean of 0 and a standard deviation of unity. Assuming homogeneous turbulence, the instantaneous velocities of air are then calculated from kinetic energy of turbulence:

$$u = \bar{u} + N\alpha, \; v = \bar{v} + N\alpha, \; w = \bar{w} + N\alpha \qquad (5)$$

where N is the pseudo -random number, ranging from 0 to1, with

$$\alpha = \left(\frac{2k}{3}\right)^{0.5} \qquad (6)$$

k is the turbulent kinetic energy.

The mean velocities which is the direct output of CFD determines the convection of the particles along the stream line, while the turbulent fluctuating velocity, $N\alpha$, contributes to the turbulent diffusion of the particle. In fact the time that the particle interacts with the any given turbulent eddy depends on speed of the particle and the life of the Eddy, so the turbulent contribution has to be recalculated accordingly.

Model for Impingement of Particles on Solid Surfaces

The program can either consider particles to bounce or stick when the hit a solid surface. For this application, since the particle is a droplet, when it is calculated to have hit a solid surface, the droplet is defined to stick to the surface, and is effectively eliminated from the calculation. The droplet is no longer considered to receive any further UV dose. There is no research to suggest that the particles would re-aerosolize, or detach from the surfaces. Further, the risk of infection from surface contact has not been considered, again due to lack of available literature.

Model for Killing Bacteria

As the droplets travel around the room they may pass through the UV beam. The beam itself has to be limited to high level for health and safety reasons, so the dose will depend on the actual path each droplet takes. The percentage survival (figure 1) is dependent on exposure to UV dose, defined as:

$$\text{Dose} = \text{Exposed time} * \text{UV Irradiance} \qquad (7)$$

This is then used to generate the probability of survival.

The percentage of survival can be written as a function of the dose as follows:

$$\%\,Survival = 100 \times e^{-kIt} \qquad (8)$$

Where I = UV irradiance, $\mu W/cm^2$
t = time of UV exposure
k = the microbe susceptibility factor, $cm^2/\mu W.s$ (k = 0.00384)

In practice the dose varies as the droplet moves trough space and so this becomes an integral of I with respect to time that can be calculated numerically.

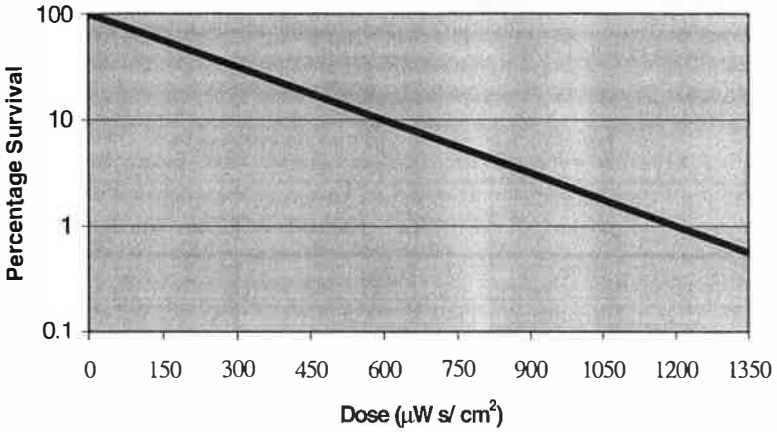

Figure 1. Survival Fraction vs. Dosage for M. tuberculosis (ASHRAE Transactions 1999, V.105 Pt. 1)

APPLICATION AND CONCLUSIONS

The application of this technique, to the design of isolation rooms itself, presents significant scope for a paper and cannot be fully documented here. The National Institutes of Health has undertaken a substantial work programme on this subject and this work has been submitted for presentation as a paper at the ASHRAE 2000 meeting (Memarzadeh, 2000).

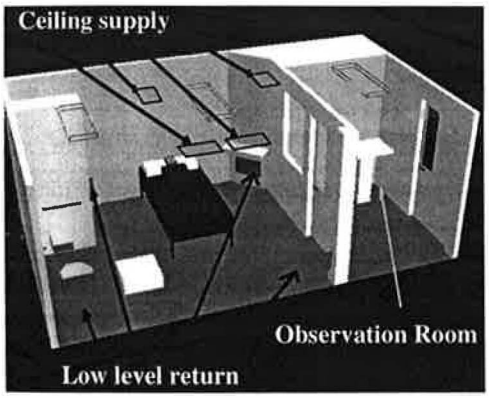

Figure 2. Isolation Room Geometry

Results are presented for four different ventilation strategies. The design as shown in Figure 1, and with an additional return placed on the wall above the head of the bed. Each configuration was run at 2

The room, figure 2,show represents a typical isolation room with wash / toilet areas and an observation room. It is classically ventilated by laminar flow air terminals in the ceiling providing downward flow to return air grilles located at low level on the side walls. The data here show that UVGI can be used to supplement the protection provided by the ventilation system. UVGI is provided by a fitting at high level providing a shallow beam covering the whole area of the isolation room itself, figure 3.

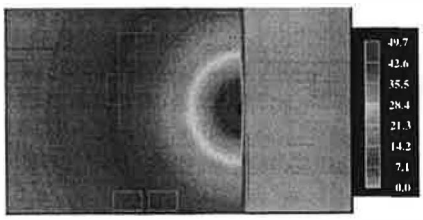

Figure 3. UVGI Intensities (μW/cm²)

ventilation rates. For simplicity of presentation the effect of UVGI is interpreted as bacteria killed after receiving a total dose of 500μW/cm^2. For each simulation the number of droplets that have received a dose of >500μW/cm^2, ventilated from the room, and still alive after 300 seconds. The methodology clearly predicts that UVGI has a significant benefit with between 5 and 15% receiving a dose greater than 500μW/cm^2. As a proportion of those remaining unventilated this is an important contribution of between 35% and 60%.

TABLE 1

DROPLET STATUS AFTER 300 SECONDS

	State after 300 secs	Number of Particles	Mean Life Time/s	Occupied Zone Time/s	Mean Dose /(μWsec/cm^2)
Traditional Low Level Exhaust 14.2 ACH	Killed	383	92	34	500
	Ventilated	1749	123	61	24
	Still alive	568	300	135	36
Traditional Low Level Exhaust 18.4 ACH	Killed	260	129	60	500
	Ventilated	1982	119	56	78
	Still alive	458	300	136	102
Local Exhaust 11.4 ACH	Killed	157	120	68	500
	Ventilated	2399	71	41	77
	Still alive	144	300	183	64
Local Exhaust 17.0 ACH	Killed	142	97	51	500
	Ventilated	2458	60	35	65
	Still alive	100	300	167	60

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