PARTICLES SIMULATION AND EVALUATION OF PERSONAL EXPOSURE TO CONTAMINANT SOURCES IN AN ELEVATION SPACE

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Summary
An elevator, which figures a small volume, is normally used by everyone for a short period of time and equipped with simple ventilation system..Any contaminant released within it may cause serious problem. This research adapt a fire and smoke simulation software (FDS) into non-fire indoor airflow scario. Differently from previous research, particles are chosen as a risk evalution unit. A personal and multi-personal exposure model is proposed. The model takes the influence of the human thermal boundary, coughing, inhalation, exhalation, standing position, and the fan factor into account. The model is easy-to-use and suitable for the design of elevator system in practice.

1 Introduction

1.1 Indoor air quality
Since the end of the 19th century new techniques made it possible to build higher and deeper buildings which applied artificial ventilation system to create an indoor environment largely independent of outdoor conditions. Although a comfortable indoor climate can be expected, the unseen and insensible contaminant airflow are often neglected by the people spend most of working hours indoors. Any pollution problem of air could cause health problems within shared working spaces and circulation spaces.

1.2 Epidemiological studies on airborne respiratory diseases
The transmission of an infection, depends on all the following factors (Kowalski 1998)
Susceptibility of the individual (immunity)
- Duration of Exposure
- Concentration of Infectious Agent
- Virulence of Infectious Agent
- Breathing Rate
- Route of infection (inhalation, eyes, nasopharynx, etc.)

None of these factors is necessarily an absolute determinant. Health and degree of immunity are hardly expressed at present technology. Some epidemiological studies show how duration and proximity to an infectious person can increase the likelihood of infection, suggest that there may be a threshold distance beyond which risk decreases sharply (Kowalski 1998). This situation is well simulated with numerical model of airflow(Nielsen 2002) and the threshold is about 1.6m. This risk may result from local airborne concentrations, but may also include the risk of contact with contaminants.In indoor airflow analysis, displacement ventilation system may blow most of contaminants away or keep the same exposure risk. Others (e.g. mixing ventilation system) will make the risk depends highly on the location of the person, local obstacles, heat sources, movements of the person, contaminant sources, etc. (Brohus 1997)

1.3 Health elevation space problems

In the high rise building environment, vertical communication system (i.e. elevation and stair) mostly shared with every occupant. Its air quality becomes a critical issue in disease control and public healthy. Numerical epidemiological investigation cases of disease outbreak have proven deeply related with small elevation space. An elevator-related health problem is often ignored. An elevator, which figures a small volume, is normally used for a short period of time and equipped with simple ventilation system (1 or 2 fans). In reality, it is used by everyone, is difficult to trace who the uses were, and features an almost closed space with limited amount of air exchange. The complexity makes it a black hole in health-related space management.

2 Aims

The purpose of this paper is to present the behavior of the particles in terms of the allocation of the infection source, the number of inhaled/attached/expelled particles, the allocation of fans, and the direction of airflow as a means to evaluate personal exposure to contaminant sources. Computer simulation of building performance in ventilation design has a strong influence to predict the movement of the particles within a space. This study applied a different approach by using software which was designed for the simulation of fire and smoke to study the movement of particles, which can be a type of disease carrier, coughed from the mouth of a pseudo infection source within an elevator. Measurement tool and simulation tool are two important tools available to determine and predict indoor contaminant particles air flow pattern. With regard to measurement, focus has been set on contaminant particles measurement techniques. With regarding to simulation, FDS 3 is found to be helpful in predicting indoor contaminant particles airflow using Computational Fluid Dynamics (CFD).

3 Theory and Methods

3.1 CFD modeling of room airflow /CFD and airflow

Computational fluid dynamics (CFD) simulation models have been used to predict room air motion since the mid-1970s. Since they provide a very detailed prediction of velocities, temperatures, and species concentration in rooms. CFD models are potentially useful for many types of building analysis (Awbi 1991): air jets, air flow in rooms, contamination dispersal and fire and smoke spread. In respiratory disease research CFD even application well in fluid flow simulation within human upper respiratory system (Nielsen 2002; Yu 1998).

3.2 The Fire Dynamics Simulator (FDS) program

A free-download program named Fire Dynamics Simulator (FDS) is used. FDS announced in 2000, according to its naming and developers originally written for fire simulation. FDS can be treated as a simple large eddy simulation (LES) model for studying the transport of smoke, heat and particles during an fire in an enclosure space. Besides FDS do batch numerical calculation, another software Smokeview (Forney and McGrattan 2003) supports the interactive visualization of output data. After carefully comparison with the experimental data, FDS could be useful to model non-fire room airflow problems (Musser 2001). Numerical model description can be found in McGrattan’s study (McGrattan 2002a).

3.3 MODEL SETUP AND SIMULATION SETTING

This study was made to the elevator located in a campus building of nine stories high. While the Department of Architecture is located at the seventh and ninth floor, the traveling time from ground floor to the ninth floor, 40 seconds approximately, was applied as the duration of simulation. The elevator cabinet is 1.6 meters wide, 1.5 meters long, and 2.25 meters high. In order to simplify the types of occupancy, the cabinet is divided into four regions that represent where the source of infection and other occupants will be located (see Fig. 1). The types of occupancy are classified into two and four persons. Since the shape of cabinet is symmetric, the source of infection can be located either in front or in back. Each case was presented with or without ventilation fan blowing air downward.

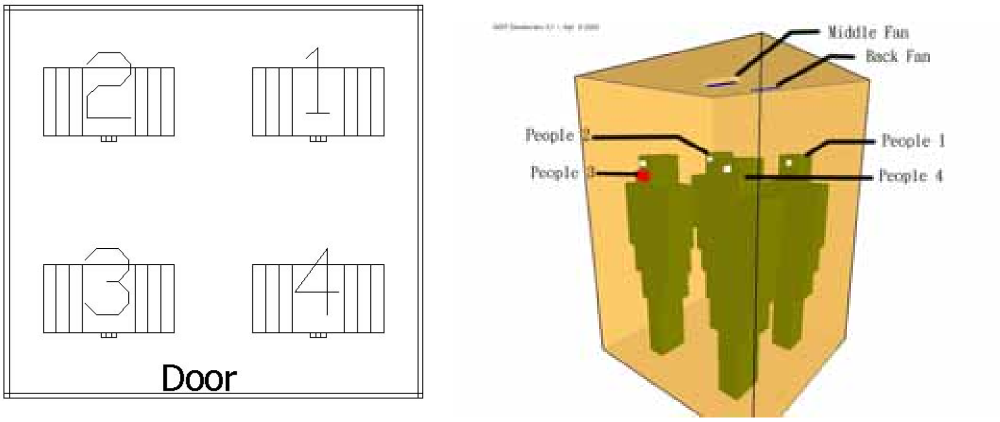


Figure 1. Floor plan and perspective view of elevator cabinet and people

3.3.1 Basic Concept and Assumptions

Six assumptions were made:

1.Particles simulation is better than concentration simulation. Recently particle tracking and path are wildly used in research (Alani 2001; Memarzadeh 2000,2002; Yu,1998). Visualization of particles path also very useful for ventilation design, communication and diagnosis. The translation between concentration and particle number can be easily achieved, in terms of number or mass of particles per unit volume. A common unit of particle count is mppcf (millions of particles per cubic foot) and of mass density is mg m^{-3} (Awbi 1991).

2.The particles or droplets generated from FDS can be treated and simulated as any contaminant such as smoke, bacteria and flavor.

3.Human breathing and coughing mechanism can be well simulated as ventilation in FDS.

4.The particles or droplets from breathing or coughing are transported by convection of the airflow can be well simulated as heat convection in FDS.

5.The particles or droplets from breathing or coughing are transported also by the turbulent diffusion of the airflow can be well simulated as turbulent effects in FDS.

6.The particles or droplets are light enough and in small quantities, that they cannot exert an influence on airflow. Therefore, the distributions of air velocities and the turbulent parameters can be directly applied to predict the distribution of the droplets.

3.3.2 Human Geometry

The computer-simulated person (CSP) is about 170 cm height which head, chest, stomach, upper and lower part of leg are modeled separately (see Fig. 1).

3.3.3 Simulation domain and grid size

The geometry of the test elevator space is model with 15 persons or 1000 KGs capacity. The operation speed is 1m/second. Because FDS uses a Poission solver based on Fast Fourier Transforms (FFTs), the dimensions of the grid should each be of the form 2^{l}x3^{m}x5^{n}. 40x40x60=96000 grids were used to cover the elevator space. Due to the small size of mouth and nose in relation to the overall size of the cabinet, grid refinement was needed (Musser 2001). Piecewise linear refinement (McGrattan 2002b) of the X-axis was used. The nose was represented by one cell and the mouth was represented by four cells after transformation.

3.3.4 Boundary conditions
The metabolic heat production was 1.7 Met (100.4 W/m^2). But it is too small comparing to heat release rate of fire. This research replaced it with body temperature (36 or 38^{o}C) under a normal or fevered condition. For simplicity the whole body has the same temperature. The elevator was non-air-conditioned and general temperature was 28^{o}C.

3.3.5 Ventilation
There are three kinds of ventilation conditions which affect the airflow within an elevator. The most influential one is the fan located in the ceiling. The second type is the cough generated by a sick person. Respiration, as the third type, is generated by every person within the elevator. Generally human respiration and coughing is a weak buoyant jet with a pulsating, intermittent nature and an initial surplus temperature (Bjorn 2002). The difference between respiration and coughing are: direction, velocity, frequency and position. A detail description is illustrated in Tab. 1. The velocity of fan and coughing are measured from field survey. The reference of respiration velocity comes from Murakami (2002). Blowing direction was simplified into downward/upward/horizontal three conditions.

Table 1: Ventilation conditions

	X (cm)	Y (cm)	Z (cm)	Flow velocity (m/sec)	Temperature (^{0}C)	Frequency (/5seconds)	Blow direction
Fan	30	10	0	3.5	28	nonstop	downward
Inhalation	2	2	5	1.2	36/38	2 sec	upward
Exhalation	2	2	5	0.8	36/38	3 sec	downward
Cough -high vol.	6	2	5	2.5	38	0.08sec*2	horizontal
Cough -low vol.	6	2	5	1.3	38	0.2sec *4	horizontal

3.3.6 Simulation time span
40 seconds is the period of time for simulation. It is estimated as the time needed for the worst case: a non-stop flight between the ground floor and the ninth floor. .

3.3.7 Occupants position and ventilation scenario
For simplify, there are only four types of possible location where people stand in an elevator (see Fig. 1 & 2). The variation of two persons is threefold with the infection source stands in front or back. The four-person test is twofold in a similar layout, due the symmetry of the elevator space. The elevator is completely steady and lift force at lower velocity is ignored. There are no significant walks (Matsumoto 2002) within the elevator space. There is only one ceiling fan provided with two alternative locations: in the middle or back of the ceiling. Each case is named by location number and fan location. The location number for infector is followed by the location number for occupants and the fan location. “2-4 back fan” is showed in Fig. 2.

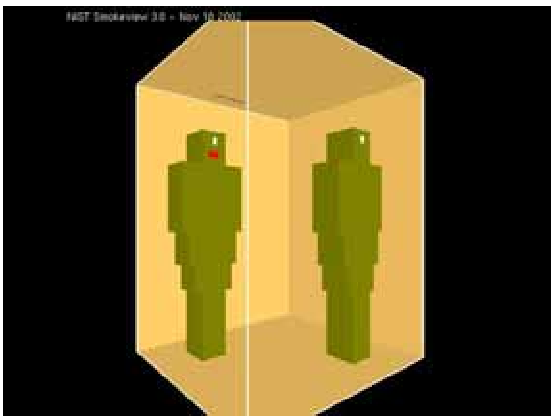


Figure 2. 3D perspective view of elevator cabinet in case 2-4 back fan.

3.3.8 Personal exposure risk assessment

Personal exposure risk is defined by the contaminant in the inhaled air. The inhaled contaminant obviously comes from the contaminated air in the breathing zone close to the mouth and nose. In this research a simplified approach is used to treat the nose as a manner of fan-in and fan-out interchanging ventilation. The capture (inhaled) velocity near the nose is about 1.2 m/sec and the exhale velocity is about 0.8 m/sec (Murakami 2002).

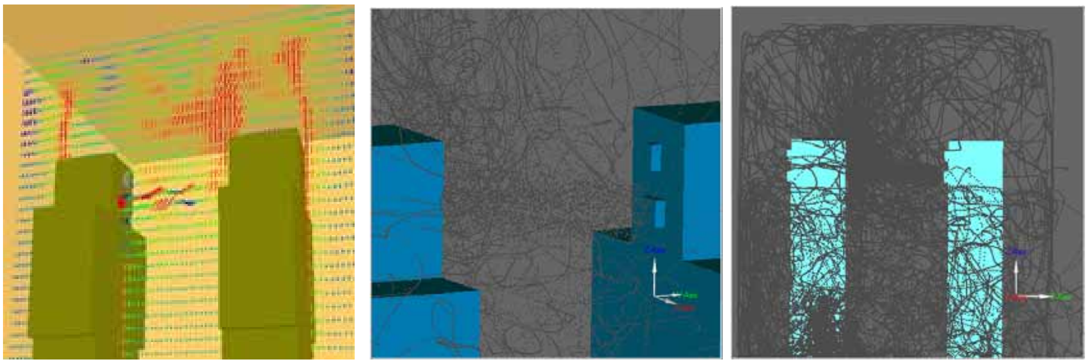


Figure 3. Flow field around head and chest(left). Particle path generation by Geometric Studio(middle and right).

4 Results

4.1 Ventilation system type

The elevator is a mixing ventilation system, because cool and fresh air is supplied from outside the elevator space with a high velocity fan. Although assumption of completely mixed room air without concentration gradients is widely accepted, the local airflow field around the occupants highly depends on the location of the person, local obstacles, heat sources, etc. Fig. 3(left) shows the flow field around head and chest. The effects of a person in a small-ventilated room may change local flow field. A person may act as an obstacle to the airflow field. This will change the direction of flow field. The heat and temperature release from human body generates a rising convection air field along the body. Heat is lost in two manners: radiation and convection. It may entrain a lower contaminant to the person.

4.2 Airflow pattern

Main and dominant airflow within an elevator space is the wind brought by fan. The airflow entrains the air current directly toward bottom, and then the current rebounds toward the ceiling. The local field is around person. Several factors should take into account:

1.The metabolic heat release from human body makes an ascending current cover the person.
2.The inhalation current, acts as only capture force to absorb contaminant, is vertically upward.
3.The exhalation current is vertically downward.
4.The coughing current, acts contaminant source, is horizontally toward the elevator door.
5.Coughing airflow pattern basically is moving forward and upward. Main obstructions that are human bodies may stop (absorbed) and change airflow (rebounded).

4.3 Particles effects

FDS generate particles binary file that contains time, particle numbers and every particles position. A post-processing FORTRAN programs was written to study particles behavior. The main function of the program is to compare particle’s number and to trace particle’s current and vanishing position. The program also supports the analysis of generation, vanishing, and absorption of particles.

4.4 Generation

During cough period FDS generates particles based on the grid number of mouth, and each coughing step releases 4 particles. Coughing velocity determines the frequency to release particles. Because FDS determinates the optimal time of each step internally, the program controlled particle number is unchangeable by the user. Percentage was used as the base reference of comparison, because the generation of particle number is slightly different in each case. Particles vanish under three conditions:

1.go-out the elevator space.

2.stick on or into human body

3.absorbed through nose or captured during inhalation period

In order to trace winded paths, it is better to rely upon particles tracing program to analyze hundreds flying around particles. Fig. 3(middle and right) and 4 shows particle paths and vanishing snapshots as an alternative manner of verification.

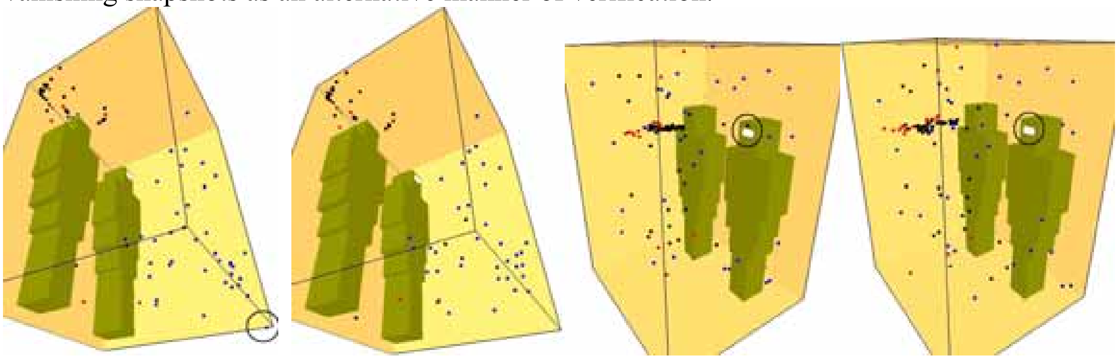


Figure 4. Particles go outside(left 2) and absorbed(right 2) in FDS Smokeview

4.5 Case description

In the beginning, there are 24 cases simulated. Cases were classified by the number of occupants, the relative location between the infector and the normal people, and the ceiling fan's location and blowing directions.

4.5.1 The analysis of the two occupants case

<u>**Case 2-4**</u>: The infector stands in location 2 and the normal person stands in location 4

The contaminant current, released from location 2, blows directly toward location 3. Most of the particles arrive at the front wall of the elevator and moving slowly along the wall. Because location 4 and 3 share the same wall, transporting to location 4 is easier than to location 2. The fan in the middle of ceiling keeps particles in location 3 and location 4, increasing the stick risk to the people in location 4. The same effect is applicable to the fan in the back of ceiling except increased distance lowers the effect. Without any fan, the flow field is more stable and the particles transport slower, upward, and well spread than the cases with fans. For the comparison of risk, stick risk (SR) is suggested.

$$SR = \frac{AP}{TP} \times 100\,\% \qquad (1)$$

Where SR is the stick risk, AP is the number of particles absorbed or stick to normal people, and TP is the total number of particles released from the infector.

$$AP = TP - OP \qquad (2)$$

Where OP is the particle number go out of the elevator. Scanning and evaluating program are developed to check particle's coordinates of vanishing near computational domain. SR is a roughly estimated index for quick acquisition of dangerous risk. In case 2-4, the highest SR value is about 4.58% under the middle fan case. SR value is 0% in no fan case, since most particles stay close to the ceiling in the upper part of the elevator, and fall down slowly.

Case 4-2:
The location of the infector and the normal person in case 2-4 is switched. The contaminant current released from location 4 blows directly toward the front wall. Particles hit the front wall and float upward slowly along the wall. By the ceiling, particles transport to location 3 and location 1. Location 2, where the normal person stands, is the farthest and the latest place to arrive at. The fan in the ceiling will rapidly blows particles downward to the ground. Without any fan, the flow field is more stable and the particles transport slower, upward, and well spread than persons stand fanned case. The SR value is quite close to case 2-4 but is lower than it.
Case 2-1:
The infector stands in location 2 and the normal person stands in location 1.The contaminant current released from location 2 blows directly toward the front wall. Particles float upward slowly before hit the front wall. By the ceiling, particles transport to location 3 and location 4. Location 1, where the normal person stands, is the farthest and the latest place to arrive at. The fan in the ceiling will rapidly blow particles downward to the ground. Without any fan, the flow field is more stable and the particles transport slower, upward, and well spread than persons stand fanned case. The SR value is quite close to case 2-4 but lower than it.
Case 1-2:
The location of the infector and the normal person in case 2-1 is switched. The contaminant current released from location 1 blows directly toward the front wall. Particles float upward slowly before hit the front wall. By the ceiling, particles transport to location 3 and location 4. Location 2, where the normal person stands, is the farthest and the latest place to arrive at. The fan in the ceiling will rapidly blow particles downward to the ground. Without any fan, the flow field is more stable and the particles transport slower, upward, and well spread than persons stand fanned case. The SR value is lower than 5%.
Case 2-3:
The infector is standing in location 2 and normal people standing in location 3. The contaminant current released from location 2 blows directly toward the front people. Particles are blown directly and hit the back head of the normal person in front. Almost all particles stop awhile, no obvious rebound off the back head. Particles float upward slowly as other cases do and transport to location 4 and location 1 along ceiling about 10 seconds later. The fan in the ceiling will rapidly blow particles downward to the ground. Without any fan, the flow field is more stable and the particles transport slower, upward, and well spread than fanned case. Since particles are blown directly and stay much longer than other cases do, the SR value is quite higher than the value of other cases as over 10%.
Case 3-2:
The location of the infector and the normal person in case 2-3 is switched.The contaminant current released from location 3 blows directly toward the front wall. Particles hit the front wall and floating upward slowly along the wall and ceiling. Particles transport to location 4 and location 2. Location 2 , where normal person stands, is the farthest and the latest place to arrive at. The fan in the ceiling will rapidly blow particles downward to the ground. Without any fan, the flow field is more stable and particles transport slower, upward, and well spread than persons stand fanned case. The SR value is quite close to case 2-4 but lower than it.
After comparison, case 2-3 and 3-2 are the highest SR value and further studies are made.

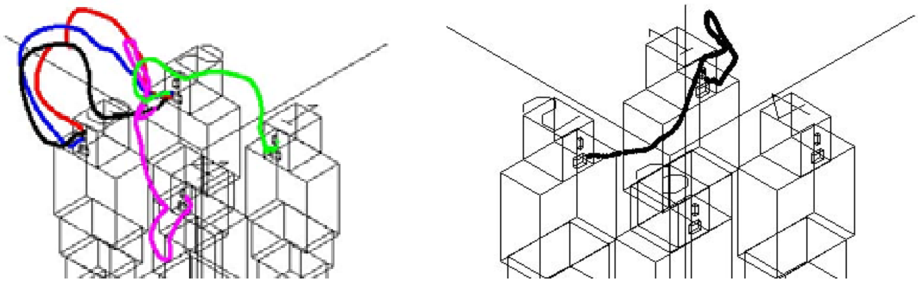
4.5.2 The analysis of the four occupants case

Case 2-134:
Similar to case 2-3, contaminant blows toward the front person. Particles blow directly and hit the back head of the normal person. Almost all particles stop awhile. Particles float upward slowly, slightly later than the case 2-3, and transport to location 4 and location 1. The fan in the ceiling will rapidly blow particles downward to the ground. Without any fan, the flow field is more stable and particles transport slower, upward, and well spread than the fanned case. The

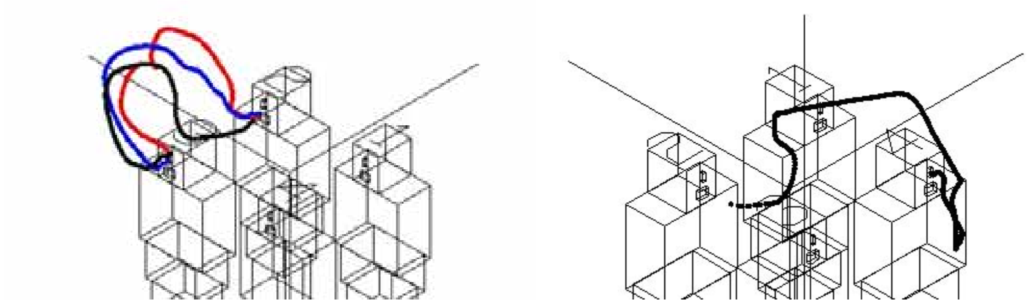
SR value is higher than others at about 15% of the middle and back fanned cases. Particles path from person 2 to others can be seen from Fig 5.

Case 3-124:

Similar to case 3-2, contaminant blows toward the front wall. Particles hit the front wall and float upward slowly along the wall and the ceiling. Particles transport to location 4 and 2. The fan will rapidly blow particles downward to the ground. Although there are more persons in the elevator, the SR value is quite close to case 3-2 but slightly higher than it's value.



particle path from person 2 to others   particle path from person 2 to person 1



particle path from person 2 to person 3   particle path from person 2 to person 4

Figure 5. paths of particles traveling from mouth to nose

5. Discussion

A personal and multi-personal exposure model is proposed. The model takes the influence of the human thermal boundary, coughing, inhalation, exhalation, standing position, and the fan factor into account. The model is easy-to-use and suitable for the design of elevator system in practice.

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