Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 10 (22): 2855-2861, 2010
ISSN 1812-5654

The Influence of Indoor Obstacles on General Ventilation Designs

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Abstract: Some real environmental aspects didn't consider in those methods or standards, such as the obstacles inside the indoor environments. Therefore, a series ventilation experimental design for the kind of environments is conducted in this study. A full scale test chamber was used for tracer gas experiments. Horizontal and vertical board-obstacles are designed for simulation the real environments. Both board-obstacles increase the heights from floor to ceiling. Total of sixteen different arrangements are examined; eight for board-obstacle vertical to the flow path and another eight for horizontal to the flow path. In addition, two different air supply rates will use to investigate the effect of air supply rate on contaminant removal efficiency. The CO_2 was used as the tracer gas and decay method was adopted to measure the CO_2 concentration of each individual sample point. Four CO_2 record trees were installed in the test chamber and each tree has two sample points. Finally, a weight factor for the obstacle's surface to chamber vertical surface or horizontal surface had found in this study help for evaluating the actual ventilation efficiency or contaminant removal efficiency.

Key words: Ventilation, concentration, tracer gas, removal efficiency, test chamber

INTRODUCTION

Using ventilation technology to control air contaminant is a common tool for an environmental engineer. An appropriate ventilation design can provide a high quality living and working environment for occupants. Therefore, to quantify emission from a building, the ventilation rate and the gas concentrations in exhaust section must be known (Kavolelis, 2003). In fact, the acceptable level for indoor air quality is specified by many countries. There are accurate measurements techniques for ventilation rate with forced ventilation have been presented by Berckmans *et al*. (1991) and Young *et al*. (1999). Including the standard test and sampling methods are developed by many research institutes. However, some real environmental aspects didn't consider in those methods or standards, such as the obstacles inside the indoor environments. Ventilation for contaminant control falls into two general categories, general exhaust and local exhaust ventilation that have been conducted by Sterling *et al*. (1985). Fume hoods and external hoods for controlling contaminant dispersal in industrial workplaces are typical examples of local exhaust ventilation (ASHRAE, 1991). These are effective where the location of the contaminant source is known and fixed. In contrast, when contaminant source locations are not known or when it is not practical to keep the source in one location, general exhaust ventilation is used appropriately to remove air from the entire ventilated space. Most health care facilities may have many sources and the source locations usually are not known. Furthermore, CDC (1994) investigated the exposed individual receivers (i.e., patients or medical staff) need to move around so that their locations are not always predicable in relation to the source locations. The contaminant control efficiency of ventilation systems is evaluated by measuring their ability to remove airborne contaminants from a space. The rate at which contaminants are removed is compared to the rate that would occur if the clean incoming air were instantly and completely mixed with the air in the room (perfect mixing). Recently, the indoor contaminant removal efficiency has been studied widely and accumulated many practical measuring techniques. In addition, mathematical models are the best tools available for prediction purpose in the field of air quality management. Subramanian and Natarajan (2006) developed a Gaussian Plume Model to determine the concentration of pollutants from point source emissions. Chen *et al*. (1988) used PHOENICS package to simulate the indoor air flow and the distribution of airborne contaminants. The results show that the increasing ACH may enhance the ventilation efficiency. The influence of opening locations (toward the

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outdoor and indoor) with different wind velocities, air exchange rates and average indoor temperature are analyzed, via CFD numerical simulations. It shows that, in different wind conditions, roofs with outdoor and indoor openings have different capabilities in air exchange and thermal environment. (Wen *et al*., 2008). In addition, tracer gas measurements are widely used (Vant and Heitlager, 1994; Boulard and Draoui, 1995; Snell *et al*., 2003; Jiang and Chen, 2003), but they mostly rely on the assumption that tracer is perfectly mixed in space and the measurement point is representative of average ventilation efficiency within the space. Therefore, measurements errors are unavoidable due to imperfect mixing of tracer gas in the measured volume. Garrison *et al*. (1989a, b; 1991) applied the N_2, CO_2 and SF_6 tracer gas to examine the ventilation efficiency. They concluded that the greater density gas such as CO_2 and SF_6 will stay at the bottom of the test chamber and the location of inlet/outlet vents play an important role to determine the ventilation efficiency. Thus, the location of exhaust vent is suggested to locate near the contaminate sources. The similar results are also found by Shen and Chang (1994). Chung and Hsu (2001) used a full scale test chamber and tracer gas technique investigated the ventilation efficiency under different air change rate and relative vent locations, the indoor air quality may influenced by inlet/outlet relative locations larger than increasing the fresh air supply rate.

When a certain amount of fresh air is supplied into occupant space, the efficiency of ventilation is a measure of the ventilation system's ability to remove airborne contamination in the space being ventilated at a given air change rate. The high efficiency ventilation systems are needed for most health care facilities, especially in high clean standard required areas, such as operating rooms. However, the high air change rate does not guarantee the high ventilation efficiency of a ventilated space. Basically, the airflow pattern will also play an important role in obtaining high ventilation efficiency in a ventilated space. In principal, airflow pattern may be characterized in terms of short circuiting, perfect mixing and displacement flow which are general terms used to describe the nature of ventilation flow pattern within a space (Sandberg and Sjoberg, 1983). When supply air enters an occupant space and exhaust directly through the exit diffuser without mixing with the contaminant in the space at large, it is a short circuiting effect. The short circuiting effect is a very inefficient form of ventilation and results in the cumulative of the contaminants in the occupant spaces. Often, the inappropriate displaced locations of supply and exhaust diffusers are the major reason to cause the short circuiting airflow pattern. Therefore, the obstacles' effect must be considered in the whole evaluation process for more understanding the indoor ventilation efficiency.

VENTILATION EFFICIENCY MEASUREMENT

The ventilation efficiency validation for a living or working environment is very important to insure the indoor air quality. Therefore, the précising measuring technique for ventilation efficiency is studying often and widely. The common and economic way is the concentration decay method by tracer gas which is adopted by the study. In addition to the obstacles within the interior space, the location of the sampling point and air supply volume are investigated as well.

The tracer gas measurements were often used to study indoor airflow patterns and indoor ventilation efficiency. For the safety and convince reasons, the following guidelines for choosing appropriate tracer gas are suggested:

- Similar density to air
- Not normally present in the atmosphere
- No toxicity
- Neither be flammable nor explosive
- Not easily be absorbed or sink
- Easily be detected at low concentration
- To a good order of accuracy

The decay concentration measuring technique is the easiest way to evaluate the indoor ventilation efficiency by CO_2 gas. First, injecting the tracer gas into the interior space and mixing well after certain of time, the CO_2 concentration will record continuously during the testing period. Then the on-site air change rate may calculate from the recording CO_2 values using the following mass balance equation.

$$V\frac{dC}{dt} + QC - QC_{in} = F \quad (1)$$

where, V is indoor volume (m^3), C is indoor tracer gas concentration, C_{in} is supply tracer gas concentration, Q is air flow rate (m^3 sec^{-1}), F is tracer gas releasing rate (m^3 sec^{-1}), t is time (sec).

The decay method was adopted in this study to evaluate the ventilation efficiency for a perfect mixing room. The concentration of tracer gas will approach a peak level $C_{(0)}$ after the CO_2 released at a certain time. Let the tracer gas releasing rate (F) equal to zero, then the air change rate may obtain from the slope of the following integral form:

$$C_{(t)} = C_{in} - \left[C_{in} - C_{(0)}\right]e^{-\frac{Q}{V}t} \quad (2)$$

where, $C_{(0)}$ is the initial concentration of tracer gas, $C_{(t)}$ is the concentration at time t. According to Eq. 2, the air exchange arte may obtain from the slop of log y-axis and time x-axis.

$$\Rightarrow \frac{\text{In}\left|C_{in}-C_{(t)}\right|}{\text{In}\left|C_{in}-C_{(0)}\right|}=\frac{-Q}{V}t \Rightarrow \frac{\text{In}\left\lfloor (C_{in}-C_{(t)})/(C_{in}-C_{(0)})\right\rfloor}{t_1-t_2}=-\frac{Q}{V}=-At+b \quad (3)$$

where, A is the slope, minus for the value of air exchange rate, b is the constant.

Equation 3 can be used to calculate the ACH_c The slope of ACH_c for the tracer gas concentration calculation are shown in Fig. 1.

Mixing factor: The major purpose of general ventilation is adopt fresh air to dilute the contaminated air inside and

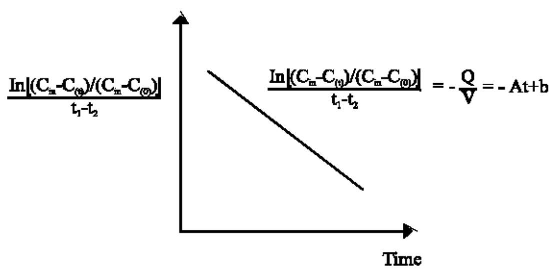

Fig. 1: The slope of ACH_c for the tracer gas concentration calculation

exhaust the mixture air Therefore, the level of air mix will play an important role for determining the air exchange efficiency.

Used the measured air volume divided by the space volume, a local exchange rate may obtain (ACH_a). On the other hand we may use the CO_2 concentrations detected on the space to calculate the local ventilation rate (ACH_c). Due to the obstacles within the real interior space, the ACH_a will greater than ACH_c usually for a not well-mixed air. The K value is defined as:

$$K=\frac{ACH_c}{ACH_a} \quad (4)$$

EXPERIMENTAL PROGRAM

A full scale test chamber was used to study the ventilation efficiency by tracer gas technology with various obstacles' design. The CO_2 sampling points are installed at the test chamber for measuring the CO_2 levels. The obstacle design is used to simulate the real living or working environment. In order to analyze test data quantitatively, the different percentage area of vertical and horizontal obstacles are designed for test as shown in Fig. 2.

Test chamber: A full-scale test chamber was used to undertake the experimental program. The well-controlled chamber size is 4.2 m height ×2.5 m width ×2.5 m height as

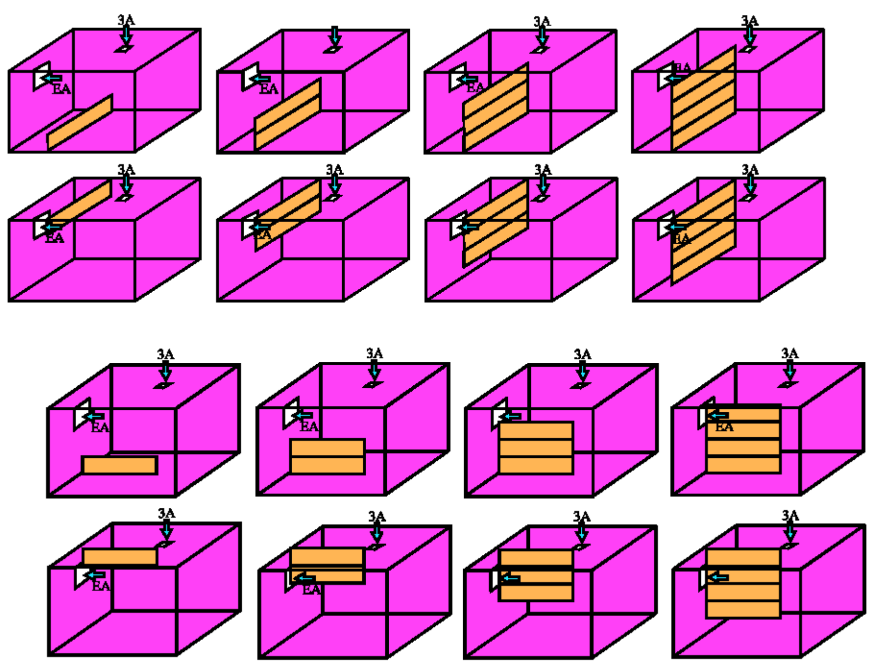

Fig. 2: The obstacle arrangement in the test chamber

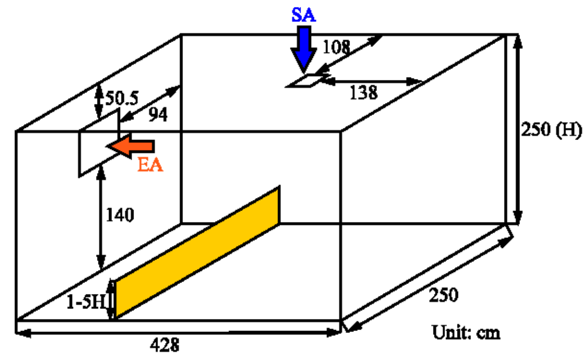

Fig. 3: Complete test chamber configuration with obstacle inside

depicted in Fig. 3. The SA means the inlet for supply air and the EA means the outlet for exhaust air.

Ventilated equipments: The various air volume fan is used to supply adequate supplied air volume to the inside of chamber. For recording the air flow rate, the air velocities were measured by hot wire anemometers in positive pressure room. Three thermal anemometer sensors were mounted on each of three iron bars which were mounted vertically to form a traverse plane. The sensors were spaced uniformly across the height and width of the room. Detailed configuration and measured locations are shown in Fig. 3. The uncertainty of velocity calibration and A/D conversion are considered to be negligible. The velocity measurements were in the range of 6 to 10 m sec^{-1} and averaging nine readings reduces uncertainty to ±1 % approximately. At lower velocity the higher uncertainty will obtain.

CO_2 measuring and recording: The CO_2 sampling points are located in M1 to M8. The CO_2 sensor measuring ranged from zero to 5000 ppm with analogy output. The CO_2 transmitters were connected to a 24 VAC supplier without an external rectifier. The CO_2 concentrations were measured by CO_2 monitors with an accuracy of ±1.5% and the monitors were calibrated with each use. First the CO_2 was injected into the negative air pressure zoom as a contaminant source. After the concentration of CO_2 gas reached an appropriate level (2000 PPM), the injection was stopped. A small propeller fan was installed in the negative air pressure zoom to ensure the CO_2 gas well mixing. Mixing was confirmed by collection and analysis of CO_2 monitors. The perfect mixing of indoor air was achieved approximately 10 min in negative air pressure room. Then the supply and exhaust fans were turned on and the opening was opened simultaneously. The measurement of contaminant of CO_2 gas began and

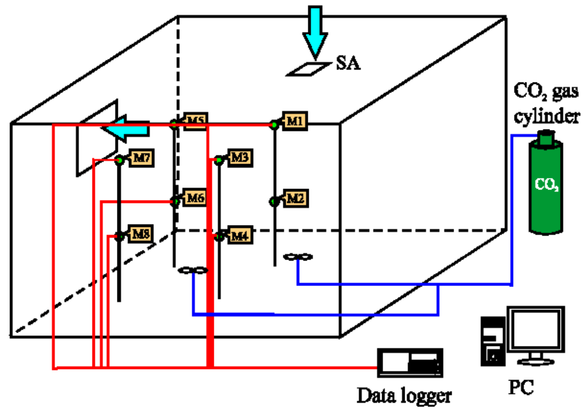

Fig. 4: The location of CO_2 sampling points and recording system

the duration of concentration sampling was about 15 min. In order to evaluate the effect of contaminant from negative air pressure area into positive air pressure area through opening when the opening was opened and resulted in instantly air pressure balance, total of eight or four CO_2 sampling points were used. The complete configuration of the experimental setup is shown in Fig. 4.

RESULTS AND DISCUSSION

The tracer gas technique is used to investigate the ventilation efficiency under various arrangements of interior obstacles. Total of 12 different test sets are scheduled for examining the vertical and horizontal obstacles within the test chamber with different inlet/outlet air volumes. The complete test parameters are listed in Table 1. The V means vertical obstacles and H means horizontal obstacles in Table 1.

In Table 1 illustrate the test parameters for test set A to L using both 6 and 12 ACH for four and eight sampling points. The CO_2 concentration distribution for 6 ACH and eight sampling points test data without obstacle inside is shown in Fig. 5 using Eq. 1-3 to calculate the slope. The slope is -0.0741 that means the ACH_c is 4.4 (0.0741×60) which less that 6 ACH_a calculated by the actual air supply volume from the inlet vent.

The ACH_c will affect by the obstacle area severely, especially in the flow stream direction as listed in Table 2. The detailed explanation of case number index is shown in Fig. 6. The larger area of obstacles it will cause the less ventilation efficiency for the obstacle standing vertically in the flow stream. The result is that the ACH_c from 4.44 will decay to 3.8 following the increase of obstacle area above from floor and from 4.44 will decay to 2.73 following

Table 1: Complete test parameters

Test No.	Initial CO_2 concentration (ppm)	ACH	Obstacle direction	Measuring locations
A	2000	6	V	8 points (M1~M8)
B	2000	6	V	4 points (M1¡BM3¡BM5¡BM7)
C	2000	6	V	4 points (M2¡BM4¡BM6¡BM8)
D	2000	6	H	8 points (M1~M8)
E	2000	6	H	4 points (M1¡BM3¡BM5¡BM7)
F	2000	6	H	4 points (M2¡BM4¡BM6¡BM8)
G	2000	12	V	8 points (M1~M8)
H	2000	12	V	4 points (M1¡BM3¡BM5¡BM7)
I	2000	12	V	4 points (M2¡BM4¡BM6¡BM8)
J	2000	12	H	8 points (M1~M8)
K	2000	12	H	4 points (M1¡BM3¡BM5¡BM7)
L	2000	12	H	4 points (M2¡BM4¡BM6¡BM8)

Table 2: The test ACH_c values of obstacle orientate vertically to the flow path at 6 and 12 ACH_a

Height of obstacle	Case No.	ACHc	Case No.	ACHc
None	CaseA6-1-0	4.44	CaseA12-1-0	6.30
1/5 H above from floor	CaseA6-1-1	4.30	CaseA12-1-1	6.24
2/5H above from floor	CaseA6-1-2	4.15	CaseA12-1-2	5.95
3/5H above from floor	CaseA6-1-3	4.06	CaseA12-1-3	5.89
4/5H above from floor	CaseA6-1-4	3.8	CaseA12-1-4	5.35
1/5H below from ceiling	CaseA6-1-5	3.87	CaseA12-1-5	6.24
2/5H below from ceiling	CaseA6-1-6	3.46	CaseA12-1-6	5.44
3/5H below from ceiling	CaseA6-1-7	3.21	CaseA12-1-7	5.39
4/5H below from ceiling	CaseA6-1-8	2.73	CaseA12-1-8	4.50

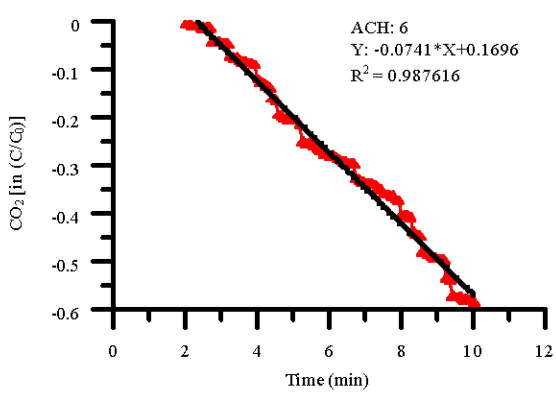

Fig. 5: The ACH_c for 6 ACH and eight sampling test case

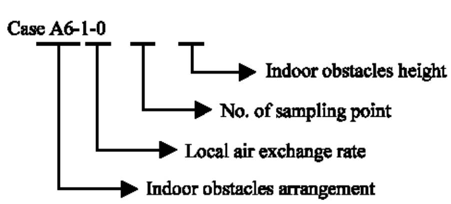

Fig. 6: Test case index illustrations

the increase of obstacle area down from ceiling under local exchange rate (ACH_a) is 6. The result show same tendency at 12 ACH_a condition, the ACH_c from 6.3 will decay to 5.35 following the increase of obstacle area above from floor and from 6.3 will decay to 4.5 following

Table 3: The test ACH_c values of obstacle orientate horizontally to the flow path at 6 and 12 ACH_a

Height of obstacle	Case No.	ACHc	Case No.	ACHc
None	CaseB6-1-0	4.44	CaseB12-1-0	6.30
1/5 H above from floor	CaseB6-1-1	4.41	CaseB12-1-1	6.24
2/5H above from floor	CaseB6-1-2	4.37	CaseB12-1-2	6.24
3/5H above from floor	CaseB6-1-3	4.27	CaseB12-1-3	6.00
4/5H above from floor	CaseB6-1-4	3.85	CaseB12-1-4	5.94
1/5H below from ceiling	CaseB6-1-5	4.39	CaseB12-1-5	6.21
2/5H below from ceiling	CaseB6-1-6	3.92	CaseB12-1-6	6.12
3/5H below from ceiling	CaseB6-1-7	3.63	CaseB12-1-7	5.70
4/5H below from ceiling	CaseB6-1-8	3.47	CaseB12-1-8	5.46

Table 4: Test results of different sampling locations for 6 ACH_a and vertical obstacles inside

Height of obstacle	ACHc8 sampling points (M1~M8)	ACHc4 sampling points (M1¡BM3¡BM5¡BM7)	ACHc4 sampling points (M2¡BM4¡M6¡BM8)
None	4.44	4.14	4.74
1/5 H above from floor	4.41	4.48	4.32
2/5H above from floor	4.37	3.97	4.32
3/5H above from floor	4.27	4.11	4.00
4/5H above from floor	3.85	3.89	3.7
1/5H below from ceiling	4.39	3.69	4.06
2/5H below from ceiling	3.92	3.57	3.36
3/5H below from ceiling	3.63	3.19	3.24
4/5H below from ceiling	3.47	2.27	3.18

the increase of obstacle area down from ceiling. The data in Table 2 also presented the obstacle above from floor will affect ACH_c more than it down from ceiling. Table 3 show the test results for the obstacle installed parallel with the flow stream. Excluding the obstacle down from the ceiling the data of the parallel obstacle test results show less influence than the vertical one. When increase the obstacle area above from floor to 4/5 height, the ACH_c only decrease 13.2% at 6 ACH_a condition and decrease 5.7% at 12 ACH_a condition. It is because the inside obstacles cause less contaminant removal from indoor to outdoor through the ventilation systems.

For evaluating the effect of number of sampling points on the ventilation efficiency, the four and eight sampling points are examined and the locations of four sampling points are also changed during the test process. Table 4 show the ACH_c for eight and four sampling points test at 6 ACH_a condition. Basically, the tested values of ventilation efficiency (ACH_c) are quite similar in the test room. However, when the sampling point close to the air supply or exhaust vent the measuring CO_2 level will fluctuate severely. Generally, the ventilation efficiency for using eight or four sampling points are similar at a closure area about 10 m^2.

Table 5 lists the K values for a single compartment with one inlet vent and outlet vent ventilation type. The K value is the ACH_c divided by ACH_a that value will always bigger than one. Referred to the test data, the upper part obstacle has greater influence on the

Table 5: The weighting K value for the vertical obstacle cases

6 ACH_a		12 ACH_a	
Percentage of the obstacle area	K value	Percentage of the obstacle area	K value
0%	1.35	0%	1.90
Above from floor 20%	1.39	Above from floor 20%	1.92
Above from floor 40%	1.45	Above from floor 40%	2.02
Above from floor 60¢H	1.48	Above from floor 60¢H	2.04
Above from floor 80¢H	1.58	Above from floor 80¢H	2.24
Below from ceiling 20%	1.55	Below from ceiling 20%	1.923
below from ceiling 40%	1.73	Below from ceiling 40%	2.20
below from ceiling 60¢H	1.87	Below from ceiling 60¢H	2.23
below from ceiling 80¢H	2.20	Below from ceiling 80¢H	2.67

ventilation efficiency than that of lower part obstacle. The bigger obstacle's area show higher K value for the vertical obstacle case. The K value may increase 3 to 6% when the 6 ACH case whereas increasing 1 to 4% for 12 ACH.

CONCLUSIONS

The study examined the ventilation efficiency using various interior obstacles' design with different air change rates experimentally. The tracer gas technology was used for analysis indoor contaminant removal rate and ventilation efficiency. Referred to the test data, the initial CO_2 concentration at 2000 and 3000 ppm did not affect the test results.

The effective ventilation efficiency may influence by the interior obstacles. Especially the obstacle located vertically at the flow path. The larger vertical area of the interior obstacles the more influence is observed in the tests. Finally, the K value is a weight factor for the obstacle's surface to chamber vertical surface or horizontal surface had found in this study help for evaluating the actual ventilation efficiency or contaminant removal efficiency.

The sampling points and locations will affect the test results. For better recording and testing results, the sampling locations are suggested taking data around the flow domain and avoiding the vent area.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support provided to this study by the Institute of Occupational Safety and Health of Taiwan under the grant No. IOSH97-H307.

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