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Tracer Decay Method for Determining Ventilation Characteristics of Naturally Ventilated Office

Ronak Daghih[1], N. M. Adam[2], Barkwi Sahari[2], Basharia Yousef[3]*, Mohd Ali[2]

[1.]*Solar Energy Reserch Institute, Universiti Kebangsaan Malaysia (UKM), 34300 Bangi, Selangor, Malaysia*
[2]*Alternative and Renewable Energy Laboratory, Institute of Advanced Technology, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[3*]*University of Bahri, Faculty of Engineering and Architecture, Department of Mechanical Engineering, P.O.Box 13104, Khartoum, Sudan.*

Abstract—*This paper presents ventilation characteristics of naturally ventilated office room that conducted at University Putra Malaysia via 14 windows-door opening arrangements. Air Exchange rate, age of air and air exchange effectiveness of a naturally ventilated office were measured and evaluated, the amount of fresh air provided to the office for each condition was calculated. Tracer gas analysis, based on concentration decay method, is employed to determine these values. Air exchange effectiveness can be employed to characterize the ventilation air mixing within a room and greatly influences the indoor air quality. Age of air is an important index to evaluate indoor air quality in rooms. Experimental results showed that the office with windows-door opening configurations performed better than the opening closed office in terms of air exchange rate, age of air and air exchange effectiveness. The results indicated air flow patterns in the occupied zone which approximate "perfect mixing" in most conditions.*

Keywords— *Air Exchange Effectiveness, Air Exchange Rate, Tracer Gas Decay Method, Age of Air, Natural Ventilation*

I. INTRODUCTION

Comfort and indoor air quality (IAQ) depend on many factors, including thermal regulation, control of internal and external sources of pollutants, supply of acceptable air, removal of unacceptable air, occupant's activities and preferences, and proper operation and maintenance of building systems. Ventilation and infiltration are only part of the acceptable indoor air quality and thermal comfort problem. Choosing appropriate ventilation and infiltration rates to solve thermal comfort problems and to reduce energy consumption can affect indoor air quality (ASHRAE, 2005). Indoor air quality in the hot, humid Equatorial climate has recently gained prominence as an issue of concern at the national and professional levels. This is evidence by increasing research reporting at major international conferences on the subject as well as the almost nonexistent national guidelines or legislation among these countries (Tham et. al., 2002).

Because of a low level of outdoor air coming into a building or poor distribution of the air in the occupied space, poor ventilation is often caused in for many cases of sick building syndrome. The distribution of the air influences both the thermal condition and the indoor air quality in the indoor space. There is a strong connection between productivity and indoor environment (Wargocki et. al., 2000 and Chung and Hsu, 2001)]. Therefore, it is important to know how efficiently the air is being distributed in the space. The basic idea behind ventilation of occupied spaces is to obtain a complete mixing of the room air. Also, the released contaminants are dispersed expectantly as a low and even contaminant distribution pattern inside the occupied room during the fresh air dilution process (Chung and Hsu, 2001).

Age of air is an important index to evaluate indoor air quality in ventilated rooms (Li X et. al., 2006). In order to assess the ventilation effectiveness, a lot of parameters or indices have been proposed, such as macro air exchange rate, air change efficiency, local air change efficiency, local ventilation index, purging air flow rate (CIBSE, 1986 and Sandberg and Sjoberg, 2005). Many of these parameters are associated with air age which is generally defined as the time that has elapsed since air element enters the room or is the mean time that it takes a particle (e.g., a molecule) to travel from an inlet point, such as the outdoor air intake, to measurement point (Sandberg and Sjoberg, 2005 and Federspiel, 1999). The (room) air age can be obtained by tracer gas technique or computational fluid dynamics (CFD) method. For the tracer gas technique, a tracer gas is related in a predefined mode and the change of tracer gas concentration with time is measured to obtain the air age (Sandberg and Sjoberg 2005; Chuan, et. al., 1999; Xing et. al., 2001). When buildings are not equipped with suitable devices for natural and/or mechanical ventilation there is no IAQ control and air changes are only due to air infiltration through the cracks and the frame of windows and doors. When the amount of fresh air supplied by air infiltration is not enough to assure a satisfactory indoor comfort the occupants themselves will, at times, operate a control by means of windows and/or doors opening (Fracastoro et. al., 2002) thus there is a need to investigate windows-door opening configuration and evaluate ventilation parameters via these arrangements. To determine the windows-door opening, performance in terms of ventilation air flow rate, 14 opening configurations have been considered. The combination of windows-door opening arrangements was carried out in an office room. The main objectives of this study are as follows:

- To assess variable windows-door opening configurations in terms of ventilation parameters, and
- To compare the acceptability with ASHRAE 62, 1989 and ASHRAE, 2005.

II. METHODOLOGY

A. Walkthrough Inspection

The objective of the visit was to identify the potential study areas and its monitoring locations within the area of interest which identified as an office room at the fifth story. Sketch of an office room is shown in Figure 1 and the overall procedures in conducting the research are shown in figure 2. Walkthrough inspection to this office was done, condition of sampling points for the measurements are the main purpose of these walkthroughs.

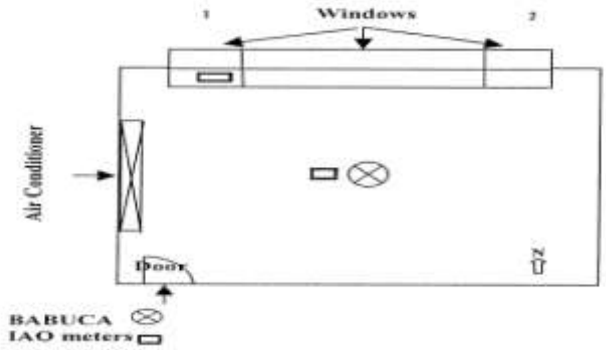

Fig. 1 Sketch of office room

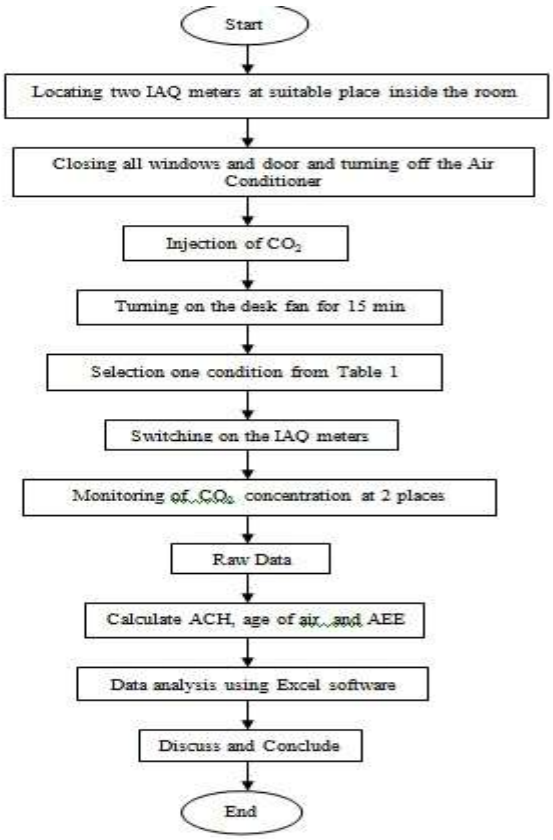

Fig. 2 Flowchart of the study

B. Arrangement of Experimental Series

The windows-door configurations were arranged in 14 different ways. Combination of windows-door opening arrangements as shown in Table 1, were carried out in office room. Experimental series were performed for the above mentioned conditions.

Table 1: **Variable Conditions of windows-door arrangements for naturally ventilated office room**

Door Position	**Windows Position**	**Code** — **Naturally Ventilated Conditions**
Closed	Two Windows Closed	A (Control)
	Two Windows Opened	U
	Windows No. 1 and No. 2 Half Opened	W1
	Windows No. 1 Fully Opened, Windows No. 2 Closed	E
	Windows No. 1 Half Opened, Windows No. 2 Closed	F1
	Windows No. 2 Fully Opened, Windows No. 1 Closed	G
	Windows No. 2 Half Opened, Windows No. 1Closed	H
Opened	Two Windows Closed	C1
	Two Windows Opened	Z
	Windows No. 1 and No. 2 Half Opened	V1
	Windows No. 1 Fully Opened, Windows No. 2 Closed	M1
	Windows No. 1 Half Opened, Windows No. 2 Closed	N
	Windows No. 2 Fully Opened, Windows No. 1 Closed	O
	Windows No. 2 Half Opened, Windows No. 1Closed	P

C. Experimental Procedures

The dimension of room is 4.10 m by 3.8 m by 2.61 m height. The office consists of three interior walls, interior floor and ceiling and one exterior wall with window area. The room was equipped with an independent air-conditioned and was fitted with one window area and one door. The dimension of the window area was 2.11 m by 2.45 m. Two bottom hung windows which were in window area with the dimensions Width x Height = 0.47 m x 1.1 m were mounted 60 cm below the ceiling. Two sampling locations were used for this experiment: One sampling location inside the room (the middle of the room), one sampling location at the system exhaust. The sampling location inside the room was at a height of 1.1 m above the floor.

The tracer gas concentration decay technique, which was a modification of ASTM Standard E741-83, describes by Bearg, 1993 was used to experimentally study air distribution and ventilation performance, because it is the method suitable for both naturally and mechanically ventilated spaces. The tracer gas decay protocol was as follows: at the beginning windows and door were closed in the room to be tested. For the test a 43 cm desk fan was placed on the floor with the exhaust side facing into the room, and at 450 angle to the wall. To measure the local mean age of air and average age of air at the system exhaust, CO2 was injected into the room and this was followed by a mixing period of 15 minutes (Cheong and Lau, 2003) to establish a uniform concentration in the air space during which desk fan was used. After an acceptably uniform initial tracer gas concentration was attained and the room air was reasonably well mixed, the tracer gas injection was stopped, followed by the window-door arrangement and a tracer gas decay occurred.

Test was conducted for each condition and all experiments were repeated minimum of several times. The precision of the test method was determined by recharging the room with tracer gas, several times for each condition and reanalyzing the decay. The mean coefficient of variation of the duplicate tests for the slope of line (slope of Naperian logarithm against elapsed time curved) for each condition was 2% (range 1-4%).

D. Instrumentation

Two IAQ meters were used to conduct the experiments were TSI's IAQ-CALC Meters Model 8760 and 8762. IAQ meter instruments simultaneously measure and data log multiple parameters to monitor indoor air quality conditions. They are carbon dioxide monitors (IAQ-CALCTM Indoor Air Quality Meters Models Product Catalogue)

III. RESULTS AND DISCUSSION

Sample graphs of the concentration-decay of the tracer-gas profile versus time are shown in Figures 3-8. The air exchanges rate, fresh air quantities,various age of air (τ) and local air change effectiveness (ε_L) are computed and tabulated in Table 2.

A. Assessment of Air Exchange rates

The amount of fresh air provided to the location for each condition is listed in Table 2, Best condition was Z and worst condition was A.

Table 2: **Measurements of Air Changes per hour (ACH) Age of air Exchange Effectiveness and Outside Air Quantities for Naturally Ventilated Office**

Middle Main Office Room							
Code	ACH	Fresh Air (l/s)[a] D=0.9AC/3.6	Design occupancy		Exhaust, τ_E (s) A	Local, τ_L (s) B	Local $\in_L$ A/B
			No. of persons (Occ) E=B[b]/10	l/sOcc F=D/E			
A	0.22	2.25	1.6≅ 2	1	2325	3060	0.76

U	2.8	28.7	2	14	1701	1620	1.05
W1	1.3	13.32	2	7	2166	2280	0.95
E	1.2	12.30	2	6	2153	2340	0.92
F1	0.42	4.30	2	2	2293	2940	0.78
G	1.4	14.35	2	7	2304	2400	0.96
H	0.61	6.25	2	3	2191	2640	0.83
C1	0.85	8.71	2	4.4	2268	2520	0.90
Z	3.2	32.80	2	16	1810	1740	1.04
V1	1.9	19.47	2	10	2246	2160	1.04
M1	2.3	23.57	2	12	1897	1860	1.02
N	1.5	15.37	2	8	2246	2340	0.96
O	2.1	21.52	2	11	2225	2160	1.03
P	1.6	16.40	2	8	2184	2100	1.04

[a] Based on an effective space volume of 90% (total volume less furniture in the office)

[b] $B = \frac{A}{H} = 15.6$ Where : A is the volume room and H is the height of office. The volume of room is A = 41 m^3 and its surface area is B = 15.6 m^2

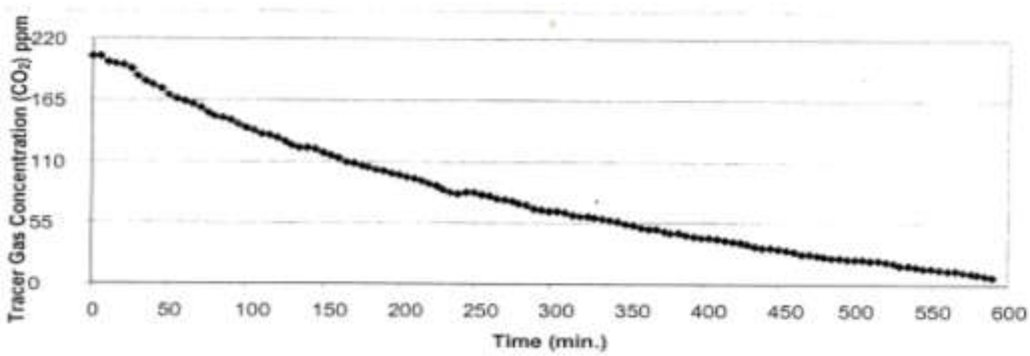

Fig. 3 Variation of Local Tracer Gas Concentration vs. Time for Control Condition (A)

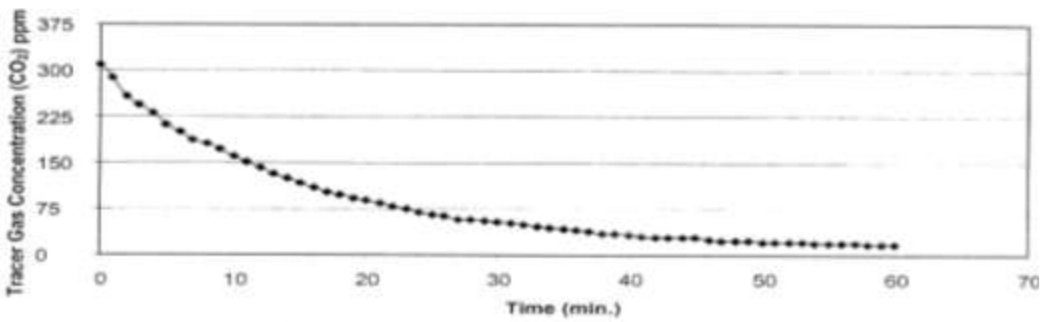

Fig. 4 Variation of Local Tracer Gas Concentration vs. Time for Control Condition (U)

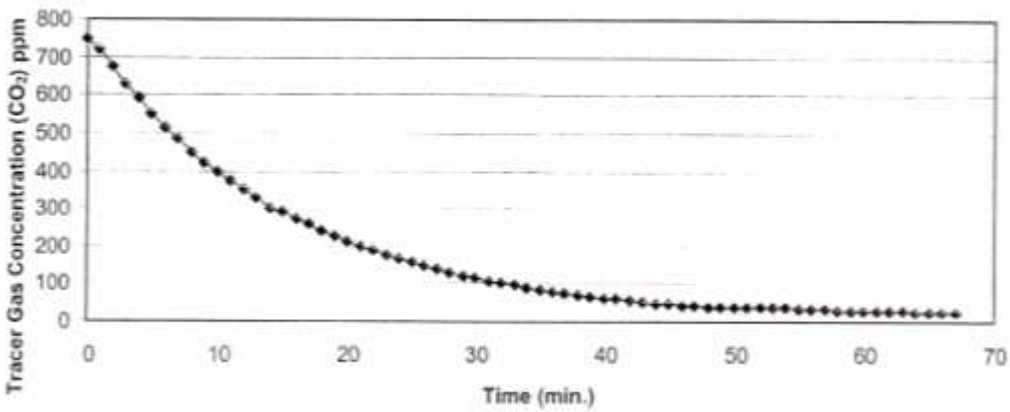

Fig. 5 Variation of Local Tracer Gas Concentration vs. Time for Control Condition (Z)

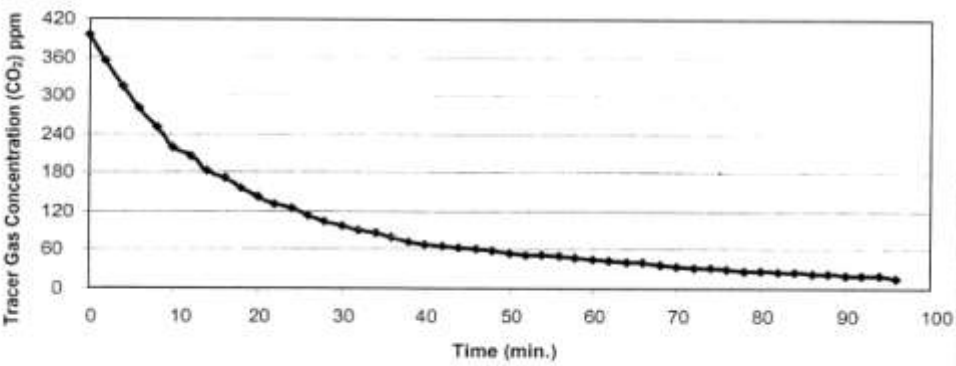

Fig. 6 Variation of Local Tracer Gas Concentration vs. Time for Control Condition (V1)

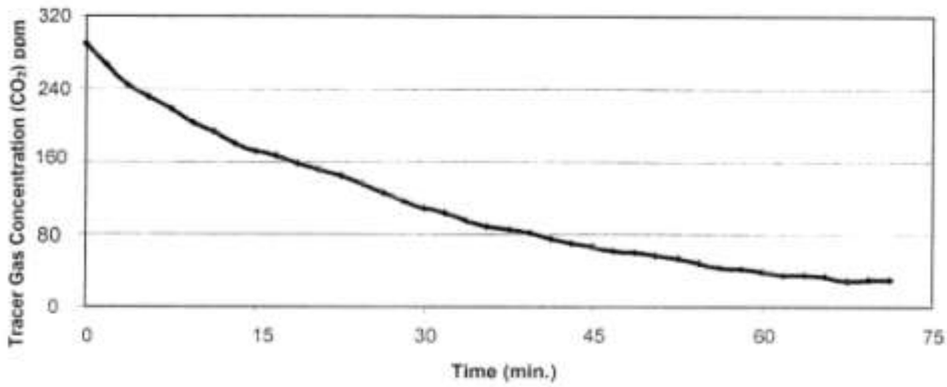

Fig. 7 Variation of Local Tracer Gas Concentration vs. Time for Control Condition (M1)

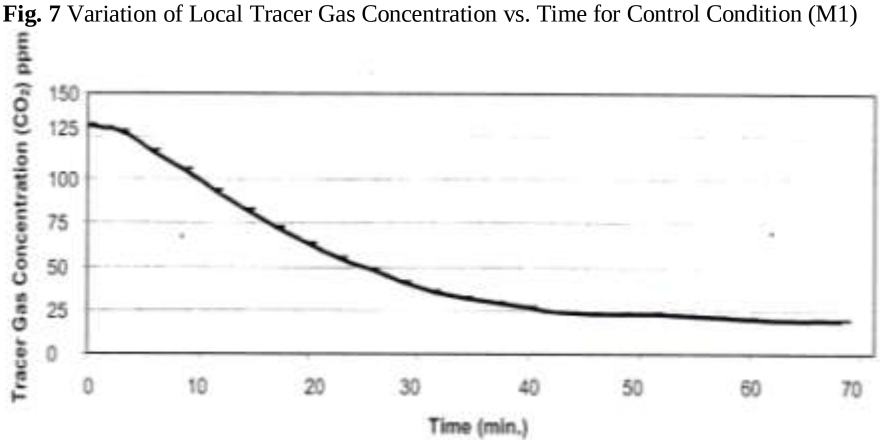

Fig. 8 Variation of Local Tracer Gas Concentration vs. Time for Control Condition (N)

The amount of fresh air provided to the middle of room for controlled condition is one (1/s)/person on the basis of design occupant density (10 m^2/person), The ASHRAE-62 requirement is 10 (1/s)/person. This indicates that the provision of outside air for ventilation is considerably lower than that mentioned by Bearg, 1993. This result showed that the office has on unacceptable air exchange rate in this condition. Inside mean air velocity was significantly low; it is in accordance with Fracastoro *et. al.,* 2002. As a result, considerably it can not be imagine enough airflow to change degree of stagnation. Inadequate ventilation will give rise to a poor indoor air quality. However, the distribution of the air over the space is just as important as the air exchange rate of the space, results obtained from the evaluation of the age of air and air exchange effectiveness showed that there was non-uniformity in air distribution.

According to ASHRAE, 2005 and Rock *et. al.*, 1995 value of air exchange effectiveness less than 1.0 shows less than mixing in office space with some degree of stagnation, When office are not equipped with suitable devices for natural and/or mechanical ventilation, in such case, there is no IAQ control and air change is only due to air infiltration through the cracks and the frame of windows and door. Obviously, in such condition the air change is only related to the stochastic behavior of the outdoor climate, When the amount of fresh air supplied by air infiltration is not enough to ensure a satisfactory indoor comfort, either from the thermal or olfactory point of view, the occupants themselves will, at times, operate a control by means of windows and/or doors opening (Fracastoro *et. al.*, 2002).

The amount of fresh air provided to the middle of roo1n for this case; window No. l was half opened, window No.2 was closed and door was closed is 2 (1/s)/person on the basis of design occupant density (10 m^2 /person). The provision of outside air for ventilations considerably lower than that mentioned by Bearg, 1993. In spite of one window was half opened in this case it has been observed that the amount of fresh air was not sufficient to meet the ASHRAE standard 62 requirements. It is expected that the main reason for this case was that the outside mean air velocity was low and it was near inside mean air velocity. The values reported for inside and outside mean air velocity was 0.08 m/s and 0.12 m/s, respectively and show low difference between them. The amount of fresh air is more than controlled condition; it is also in accordance to what (Fracastoro *et. al.*, 2002) has suggested for increasing the amount of fresh air. Open windows aid air movement and may help to cool the building and occupants in summer. Of all available controls, windows have the biggest effect on indoor climate (Raja *et. al*., 2001).

When window No.2 was half opened, Window No.1 was closed and door was closed, the amount of fresh air is 3(1/s)/person. It is considerably lower than the ASHRAE standard 62 (10 (1/s)/person). This condition is similar to condition (F1), but in this case the difference between inside and outside mean air¯ velocity is higher than condition (Fl), thus the amount of fresh air is more than that.

The amount of fresh air provided to the middle of room for this case; two windows were closed and door was opened is 4.4 (1/s)/person on the basis of design occupant density (10 m^2/person). The provision of outside air for ventilation is lower than that by Fracastoro *et. al*., 2002. It is improved with regard to mention cases; it is consistent with Lin *et. al*., 2007. The air enters the room and initially forms a layer of fresh air at office. The open door has resulted in changes in airflow pattern.

The amount of fresh air provided to the middle of room for these cases; Window No. 1 was fully opened, Window No. 2 was closed, Window No.2 was fully opened, Window No. 1 was closed and Windows No.1 and No. 2 was half opened are 6, 7 and 7(1/s)/person respectively. Door was closed in these cases. They are lower than ASHRAE, 1989, but they improved. According to Raja et. al., 2001 of all available controls, windows have the biggest effect on indoor climate. Regarding to mentioned cases, when one window is full open or two windows are half open a large influx of air from the open windows enters the office in respect to afore mention cases, so air exchange rate and the amount of fresh air are improved.

The amount of fresh air provided to the middle of room for these cases; Window No. l was half opened, Window No.2 was closed and window No.2 was half opened, Window No.1 was closed are 8(1/s)/person. Door was opened for these two cases. The open window in the office, in combination with the open door, has resulted in significant changes in airflow pattern, so the amount of fresh air is increased.

In windows No. I and No.2 half open and door open case, the amount of fresh air is 10 (l/s)/person. This indicates that the provision of outside air for ventilation is adequate in this condition, and it is in line with ASHRAE, 1989 requirements. In natural ventilated buildings the usual controls available to occupants are doors, openable Opening of doors or windows enhances natural ventilation (Raja *et. al*., 2001). The windows and doors open bear correlation with improving airflow pattern in office

The amount of fresh air provided to the middle of room for these cases; Window No. 2 was fully opened, Window No. l was closed and Window No. l was fully opened, Window No. 2 was closed are 11 and 12 (1/s) person. Door was opened in these cases, and it is in connection to ASHRAE, 1989; Raja *et. al.,* 2001; Fracastoro *et. al*., 2002; Lin *et. al*., 2007.

In the open windows case and open windows and door case, the amount of fresh air are 14 and 16 (1/s)/person and it is in accordance with ASHRAE-62 requirement. The provision of outside air for ventilation is adequate. In this case a large influx of air from the open windows and door entered the office in respect to afore mention cases, so air exchange rate and the amount of fresh air are increased more than ever. The open windows-door has resulted in considerable changes in airflow pattern. There are many researches which have been done that depict the significant influence of open windows door on enhancing airflow pattern in building (Adam, 1995; Raja *et. al*, 2001; Fracastoro *et. al*., 2002; Lin *et. al*., 2007; Rijal *et. al*., 2007; Liping and Hien, 2007; Hassan *et. al*., 2007).

B. Evaluation of Air Exchange Effectiveness

When there is a uniform distribution of air over the office air-space, ϵ_L =1. However, when there is a non-uniform distribution of air over the office air-space or in another word, some stagnant zones within office air-space, values of ϵ_L are significantly less than 1. A value less than 1.0 shows less than perfect mixing with some degree of stagnation. A value of ϵ_L>1 suggests that a degree of plug or displacement flow is present (ASHRAE, 2005 and Rock *et. al*., 1995).

The local air exchange effectiveness at location for controlled condition (A) is 0.76. Results obtained from the evaluation of the age of air arid air exchange effectiveness showed that there was non-uniformity in air distribution or there are stagnant zones within office airspace in this condition. All windows and door were closed, and air entered the room only due to air infiltration through the cracks and the frame of windows and door, the outdoor air could not come into the office easily so the age of air at this condition is old and air exchange effectiveness was less than 1.

In the window No.1 half open, Window No.2 Close and window No.2 half open, Window No. l close and door close case, the local air exchange effectiveness at location for conditions are 0.78 and 0.83, respectively. According to ASHRAE, 2005 and Rock *et. al*., 1995 these imply that there is non uniformity in air distribution or there are stagnant zones within office air-space in these conditions. It is expected that the main reasons for these cases were that the outside mean air velocity was low and was near inside mean air velocity for two conditions, and considerably it can not be imagine enough airflow to move air inside the office, so the age of air was old and air exchange effectiveness was less than 1

In other conditions the local air exchange effectiveness in the middle of room was found to be close 1, this implied that there were no short-circuiting of ventilation and suggested that a degree of plug or displacement flow was not present. The local all¯ exchange effectiveness indicated a reasonably perfect mixed air in those locations (ASHRAE, 2005).

Opening windows and door have improved air effectiveness. The air age at the windows-door opening conditions is young. This is because fresh air is drawn into the office. In general there are improvements in air exchange effectiveness in windows-door open cases.

AEE in 23 offices measured within Finland by Seppanen. AEE always exceeded 0.82 and was typically near 1.0 except in office buildings with air supplied to the hallway and exhausted from the office area. A study in several office buildings and in a research laboratory in the U.S.A conducted and obtained the air exchange effectiveness ranged from 0.72 to l. In this study, the air exchange effectiveness ranged from 0.76-1.04 and it is in connection to Fisk and Faulkner, 1993).

C. Computational fluid dynamics simulation

Figure 9 below shows the air flow distribution diagram, the CFD was used to simulate and see the air flow distribution; only one position is chosen to be simulated. The chosen position was when door and two windows are opened. This position is considered as the best position. The simulation was carried out with a commercial CFD package code name FLUENT Version 6.2. The door is defined as outlet and the two windows as mass flow inlet.

Air Change/hour for the best position when the door and two windows are opened is 3.2. The air density equal to 1.225 kg/m3, the room volume equal to 41 m3. Then the mass flow rate value which have been used in fluent software was calculated as shown below

Room air change rate = 3.2 x 41
= 131.2 m3/hour
= 0.0364 m3/s

Mass flow rate = 1.225 x 0.0364
= 0.0446 kg/s

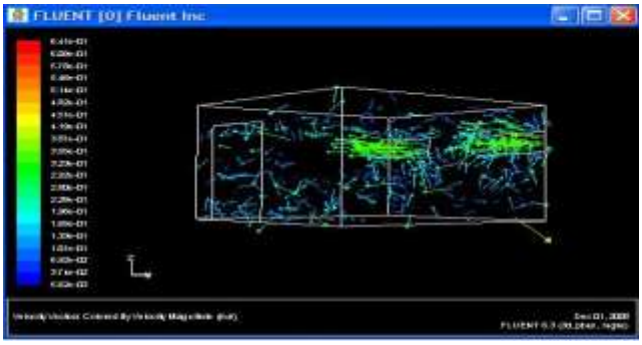

Fig. 9 Air flow distribution diagram for door and two windows opened

IV. CONCLUTIONS

The key findings from this study are as follow:

- The results of' ventilation approach indicated that windows-door openings significantly affect the airflow pattern in naturally ventilated office. The air exchange rate and mean age of air was improved in the office for the open windows-door case, due to the change in airflow pattern. When the windows or door are open the air enters the room and initially forms a layer of fresh air at office. The local air age at the windows-door opening is slightly younger. 'This is because fresh air is drawn into the office; opening of the windows-door improves airflow and air exchange effectiveness.
- Results obtained from ventilation parameters measurements revealed that the office has some ventilation problems, especially when the windows are closed. As a result, considerably it can not be imagine enough airflow to change degree of stagnation in these conditions. The air exchange rates and the amounts of fresh air provided to the office 'in most variable conditions of windows door arrangements were less than the recommended value by ASHRAE, but by opening of' windows and door air exchange rate and the amount of fresh air were improved and were within ASHRAE requirements.
- In the case of air exchange effectiveness regarding to ASHRAE, it is observed that the AEE values are usually close to one implying no serious problems of short circuiting of ventilation air in this office and that the ventilation air is well mixed.

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