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Investigation of Natural Ventilation in a Public Place in Winter Season with the Comparison of Experimentation and CFD Results

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Abstract

In educational buildings, efficient ventilation is vital for better indoor air quality and less contaminant level. High level of carbon dioxide concentration causes to drop in concentration and learning capacities of students in addition to headache, dizziness and rapid spreading of infections. In order to provide high indoor air quality; indoor temperature, carbon dioxide level, air humidity and air flow rate should be in the comfortable zone defined by standards. Natural ventilation is preferable solution since it provides improved indoor air quality with reduced energy consumption. The present study investigates the applicability of natural ventilation in the Middle East Technical University Library Reserve Section in Ankara, Turkey for desired indoor air quality defined by ASHRAE air quality standards. Temperature, carbon dioxide concentration and relative humidity data are collected during experimentation period. In the analyses, single zone model is considered. Computational fluid dynamics (CFD) analysis will are also performed for the comparison of results. Comfortable air flow rate is examined using CFD analysis. Energy saving for winter conditions is calculated. According to the results, solutions are provided for a better indoor air quality and application of natural ventilation. Experimental and numerical results clarify that natural ventilation can be used in winter times in order to reduce the carbon dioxide concentration inside the zone. Mathematical results show that there is an energy saving about 8,34 percent with usage of natural ventilation. The carbon dioxide concentration in the zone is decreased from 1147 ppm to 1000 ppm during 3 hours with the help of natural ventilation without usage of electricity. CFD results will be compared with these result.

Keywords – natural ventilation; zonal model; carbon dioxide; air quality

1. Introduction

Due to the pressure caused by temperature differences and wind, flow of outside air through the openings in building is occurred and this mechanism is called as natural ventilation. In hot and mild climatic regions, use of natural ventilation is one of the preferred strategies for architectural design in order to minimize building energy requirement [1]. The ventilation rate could be adjusted with changing arrangement of openings such as windows. For a better performance of natural ventilation, the building is designed considering annual wind and temperature characteristics [2]. Two kind of ventilation mechanisms are the single sided ventilation and cross ventilation. Single sided ventilation depends on the level of openings, opening area and discharge coefficient. Only thermally occurred pressure gradients are considered, the wind pressure effect is not considered because of single side openings [3].

Natural ventilation is an electricity free mechanism. Therefore, it is important for a sustainable energy efficient building environment. Good quality of air can be achieved with no usage of electricity for movement of air when natural ventilation is preferred [4]. According to the research in 1987 in Portuguese school buildings [5], 70% of the CO_2 content records were exceeded the standard limits for safe CO_2 concentration. High level of CO_2 concentration is occurred because of the low ventilation rates during lectures in winter to satisfy thermal comfort. Such high levels are one of the source of health problems and affect the performance of students in lectures [6, 7]. The limits of CO_2 content in a volume is described by World Health Organization for human health. The indoor air specifications should be within the recommended CO_2 limits and temperature comfort zone [8, 9].

Natural ventilation in reserve library of Middle East Technical University in Ankara Turkey for winter season with the comparison of experimentation and CFD results is investigated in the present study. The section, which has 200 student capacities, is heated by a central heating system. For providing healthy indoor air quality, there is no cooling or ventilation system.

2. Methodology

a. Theory & Experimentation

Single zone model is used in theoretical analysis in order to obtain CO_2 concentration and energy consumption of the building. CO_2 concentration and temperature inside the reserve section, outside environment temperature and occupant number are recorded during the experimentation period. The theoretical and experimental results are compared in the study.

There are 6 windows at the opposite of the entrance and 8 windows at the left side of the entrance. Windows are partially opened and are pivoted at the top. Infiltration is included in the theoretical analyses, since the sealing of the windows are not proper. The recirculation is neglected within the zone. The architectural plan of reserve section is shown in Figure 1.

Experiments are conducted in the days of final examination period because of high number of occupants. The data are collected between 10:00 am and 05:00 pm. Inside air temperature and CO_2 concentration are recorded by a non-dispersive infrared carbon dioxide sensor. The sensor element was located such that air stagnation or local heat sources would not influence the measurements and set at seated head height as required for measurements. Outdoor air temperatures are measured using thermocouple and occupant number is counted regularly. The data are collected in 30 second intervals.

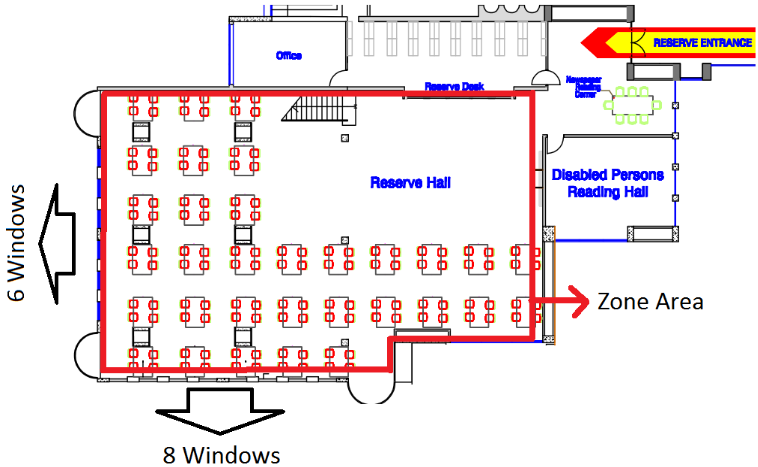


Figure 1. The plan of METU Library Reserve Section

With analyses using single zone model, one inlet and one outlet are described and temperature and CO_2 content are taken as homogenous in the volume of zone. Due to the winter season, none of the windows are open and the mass flow is occurred due to the infiltration only. The ventilation rate in terms of CO_2 concentration in literature [10] is as follows;

$$V = \frac{C_{gen}}{C_{int} - C_{est}} \quad [m^3 / h] \tag{1}$$

In equation 1; V is the ventilation rate, C_{gen} is the CO_2 generated by occupants, C_{est} is the CO_2 in the outdoor environment and C_{int} is the average of the CO_2 concentration measured in the considered time period. Considering a CO_2 production of 19 L/h per human as prescribed by EN15251 [11] and an outdoor CO_2 concentration set to 400 ppm as measured in the outside of the reserve section, Equation (1) can be rearranged.

$$V = \frac{19000\left[\frac{cm^3}{h*person}\right]*n[person]}{(C_{int} - 400)\left[\frac{cm^3}{m^3}\right]} \quad [m^3/h] \tag{2}$$

Considering the mass flow rate equation in literature [1] and Eqn. 2; indoor carbon dioxide concentration is derived.

$$C_i = \frac{19000*n}{3600*A*(0.40+0.0045*|T_i - T_o|)} * \sqrt{\frac{T_i}{g*H*|T_o - T_i|}} + 400 \quad [ppm] \tag{3}$$

In equation 3; C_i is the inside carbon dioxide concentration, A is the leakage or opening area, H is the height of the opening, n is the occupant number, T_i and T_o is the inside and outside temperature respectively.

The energy equation is also applied to the zone;

$$\rho_i * V * C_v * \frac{dT_i}{dt} = Q_{occ} + Q_{in} - Q_{inf} - Q_{out} - Q_{loss} \tag{4}$$

where, ρ_i is the indoor air density, V is volume of the zone, Q_{occ} is the heat from occupants, Q_{in} is the heat from central heating system, Q_{inf} is the infiltration loss, Q_{out} is the heat loss due to window opening and Q_{loss} is the heat loss from walls. Q_{occ} is taken as 117 W per person for seated and very light work condition [1]. Q_{inf} and Q_{loss} are expressed as;

$$Q_{inf} = \dot{m} * C_p * (T_i - T_o) \tag{5}$$

$$Q_{loss} = UA * (T_i - T_o) \tag{6}$$

b. Computational Fluid Dynamics Analyses

The URANS simulations are performed for predicting the variation of spatial CO_2 mass fraction distribution with time. The computations are performed by using the commercial software package ANSYS Fluent 15.0. The computational domain as a 20000 m^3 volume with proper meshing is presented in Figure 2.

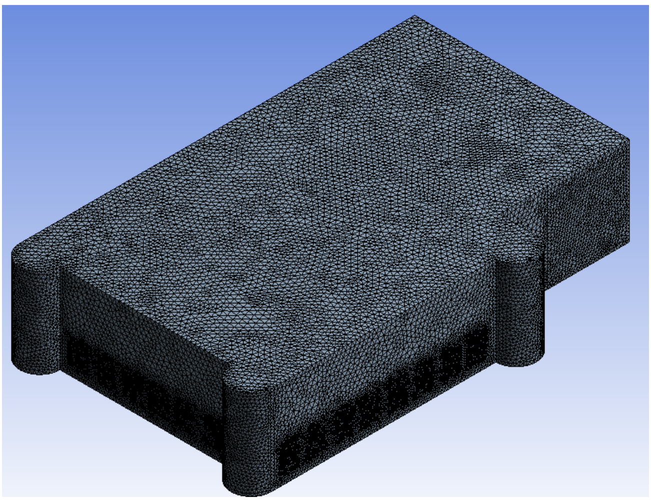


Figure 2. Computation domain for CFD Analyses

The computational grids used in the URANS simulations are composed of approximately 600000 tetrahedral and prismatic volume elements. In the grids, prismatic elements are used in the vicinity of the walls for increasing the resolution and mesh quality. A 3D pressure based solver is preferred in which SIMPLE method has been preferred for pressure-velocity coupling. The transient analyses performed for 24000 seconds. Fluid media is assumed to be a mixture of air and CO_2. Incompressible ideal gas model has been employed for modeling the mixture density variation with temperature since the effect of natural convection is also accounted in the analyses. In the URANS simulations standard k-ε turbulence model has been activated. The inlet boundary is defined as a “mass flow inlet” for simulating the infiltration of air from outside. Mass flow and temperature variation at this boundary is defined as a function of time, which is obtained by fitting a polynomial function on the measured data. The inlet mass fraction of CO_2 is assumed to be constant and equal to 6.11E-04. The outlet boundary is defined as “pressure outlet” with a gage pressure equal to the ambient. The volumetric mass generation of CO_2 due to occupants is also defined as a function of time by fitting a polynomial function on the calculated CO_2 generation value. An overall heat transfer coefficient of 2.15 W/m^2K is used in energy balance analysis. Moreover, constant volumetric heat generation of 7 W/m^3 is defined to the fluid domain for stabilization of the fluid domain temperature. In computations spatial discretization is made by using second order upwind-type schemes. The temporal discretization for all cases is made by using a first order scheme. The time step size is chosen accordingly, to satisfy the residual convergence on the order of 10^{-4}.

3. Results and Discussion

The calculations are performed for indoor CO_2 concentration, and the findings show that it can be possible to figure out the variation in CO_2 concentration. Theoretical and experimental CO_2 concentration with the change in occupant number is presented in Figure 3. In experimentation day, the library has reached the full capacity with number of 200 students.

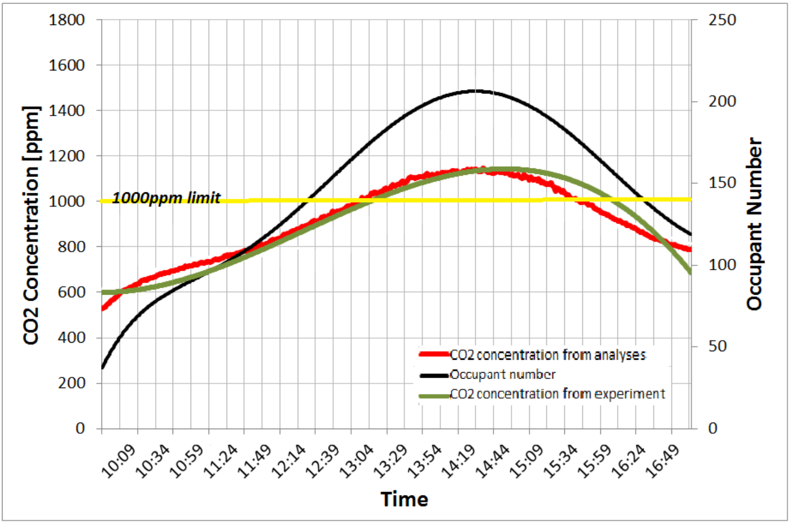


Figure 3. Theoretical and experimental CO_2 concentration and occupant number

Figure 3 revealed that, the limit value of 1000 ppm for CO_2 concentration has been exceeded about 3 hours within the library reserve section when the occupant number is more than 120.

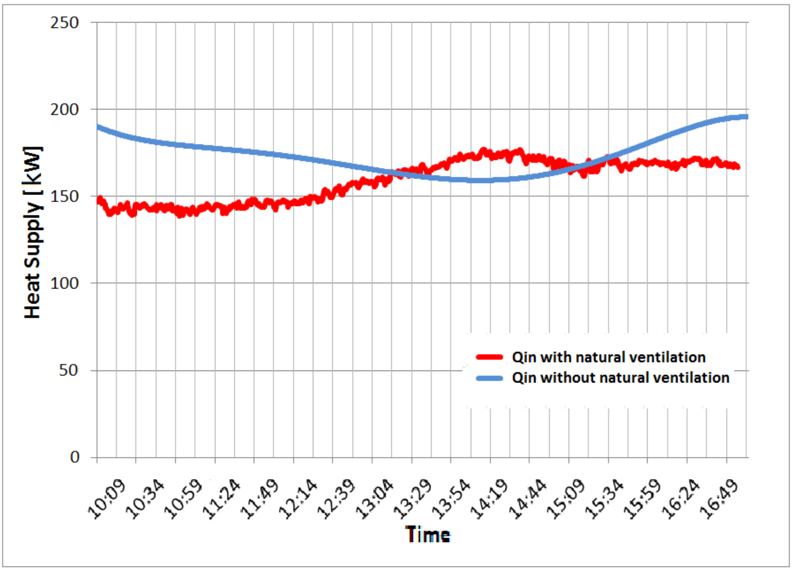


Figure 4. Heat supply with and without usage of natural ventilation

Experimentation results clarify that the indoor air temperature is held at an average value 22°C by with the help of a central heating system. Therefore, Q_{in} value is changed according to the other parameters. Using single zone model and the energy equation, the Q_{in} value is obtained for the experiment period. Considering the 1000 ppm limit of carbon dioxide concentration standard and using the mass balance and energy equations, the necessary opening area is obtained for the experiment period. If the windows were sealed well and keeping CO_2 concentration less than 1000 ppm with the opening of window, there is energy saving about 8.34%. The result is presented in Figures 4 and 5.

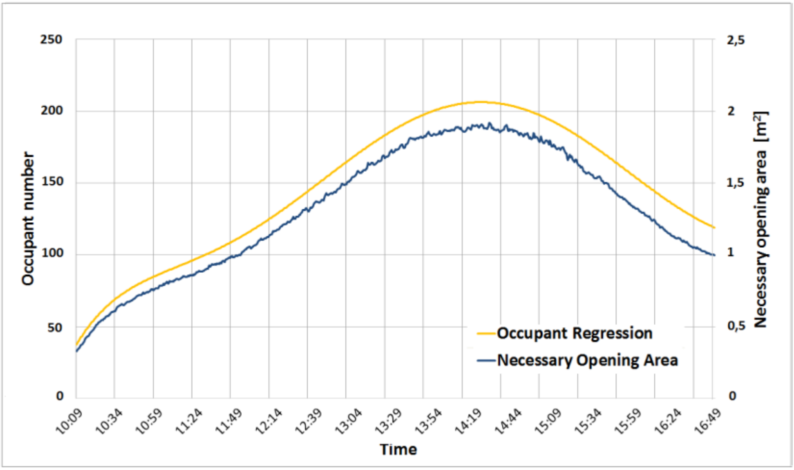


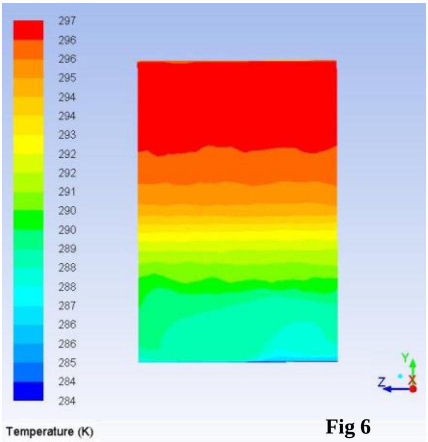
Figure 5. Necessary opening area of windows for desired indoor air quality

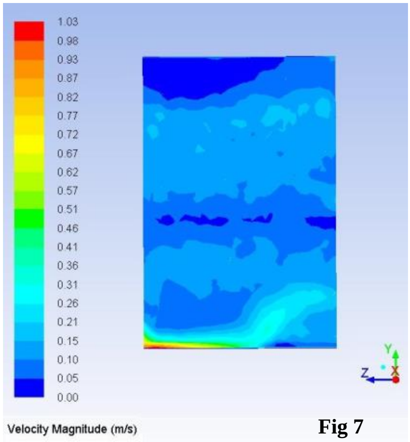
The peak levels of CO_2 concentration from experiment and theoretical analyses are presented in Table 1. As shown, the concentration levels are exceeding the limit value (1000ppm) which is not healthy and comfortable for student study in library.

Table 1. The peak level of carbon dioxide concentrations

The peak level of CO_2 concentration				
	CO_2 concentration	Occupant number	Peak Time	Exceeding Duration
Experiment	1147ppm	206	14:32	2:50h
Analyses	1140ppm	206	14:36	2:40h

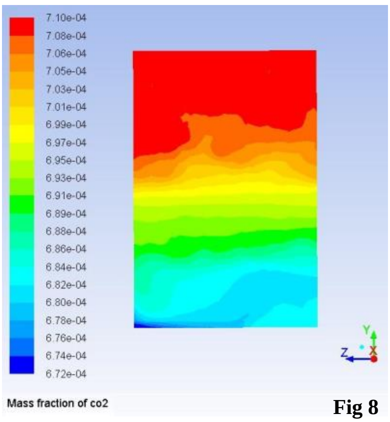
Results of CFD analyses including temperature and velocity profiles in vertical mid-plane of the domain are presented in Figures 6 and 7 respectively.

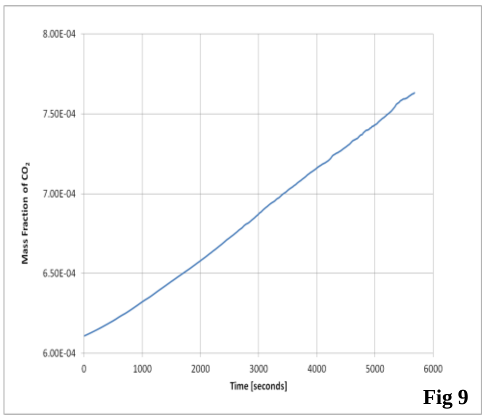




Figures 6&7. Temperature and velocity distribution contour plots at the mid-plane cross section at time 3390 sec

Results show that there is temperature stratification within the domain. The velocity contours indicate the direction of flow of infiltrated air from the windows. The maximum velocity value of air in the vicinity of windows does not exceed 1 m/s with a small amount of mass flow in.





Figures 8&9. Mass fraction of CO_2 distribution contour plots and CO_2 mass fraction variation with time at the mid-point of fluid domain obtained from CFD analysis

As presented in Figure 8; CFD results also reveal that the average CO_2 mass fraction value within the zone at the end of the first hour is about $7x10^{-4}$. The result is consistent with the experimental and theoretical CO_2 concentrations inside. CO_2 mass fraction variation with time at the mid-point of fluid domain is presented in Figure 9 for the very first one hour of the transient CFD analysis. Obtained result in Figure 9 can be compared with the general trend of CO_2 concentration determined in experiments, presented in Figure 3. The comparison performed for the very first 60 minutes results in experimentation shows a proper agreement between the experimental and numerical results.

4. Conclusion and Suggestions

Comparison of experimentation and CFD results for applicability of natural ventilation in order to satisfy acceptable indoor air quality in METU library reserve section is investigated in the present study. Carbon dioxide concentration is measured during the experiment and later it is calculated and the consistency is compared. The results show that the CO_2 concentration in the air is determinable with theoretical analyses as occupant number and temperature are main inputs. Zonal model is preferred for theoretical analyses because of simplicity and providing a valid approach.

The source of the errors can be counted as the measuring device (which has a tolerance of ±50 ppm), the counting of occupant number, the all assumptions, calculation, the wind in the outside and the environmental effects.

Experimental and numerical results clarify that natural ventilation can be used in winter times in order to reduce the carbon dioxide concentration inside the zone. As a result, the energy efficiency of the building is increased with preventing of infiltration and using natural ventilation. Natural ventilation can be easily obtained with changing the opening area of the windows. An automated system can be used in order to provide the necessary mass flow rate with the adjustable windows resulting in energy saving and desired indoor air quality.

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