J. Appl. Environ. Biol. Sci., 6(1)151-174, 2016
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ISSN: 2090-4274
Journal of Applied Environmental and Biological Sciences
www.textroad.com

Modeling and Assessment of Indoor Air Quality in Residential Units

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Received: July 8, 2015
Accepted: October 20, 2015

ABSTRACT

Inappropriate design and use of air conditioning systems not only increase consumed energy of building, but it decrease thermal comfort and indoor air quality problems. If incoming air distributor has not been installed in an appropriate place, fresh air may not be able to be fully ventilated and old air may remain in some regions. Reports of World Health Organization (WHO) indicate that low quality of indoor air causes to the increase of respiratory diseases, allergy and asthma. Forecasting air flow within building and the amount of heat and pollution transfer can provide useful information for engineers to design optimal air conditioning systems. Also, developing a reliable and affordable method for such forecasting is very important. Knowing about inside environment influences people' life in three ways: thermal comfort, indoor air quality and energy consumption of building. The present paper attempted to determine characteristics of air flow as well as pollutants exiting from fireplaces without chimneys through numerically simulation. Two different rooms are simulated and their results provided in profiles of temperature change, radiation temperature, relative humidity, speed and distribution of pollutants.
KEYWORDS: Indoor air quality , thermal comfort, Air pollution

INTRODUCTION

Thermal comfort refers to the conditions in which feeling of satisfaction is resulted by the temperature of environment [1]. This definition indicates that the thermal comfort is the result of environmental indices. The thermal comfort of environment influences the individuals' efficiency by physical and environmental factors. To create thermal comfort and increase the efficiency, the environmental indices such as the air speed, temperature and humidity should be at the appropriate ranges. Considering the fact that the external environment conditions can cause important effects on the indoor air conditions, the appropriate natural or mechanical ventilation systems should be applied in building to reach the target conditions in internal space.

Furthermore, the thermal comfort of indoor air quality has also a critical impact on the residents' health and welfare. Most of the offices and houses use the furniture, paintings, carpets, etc. which can emit large particles such as the volatile organic particles into the environment. These emitted particles have harmful effects on the human health. The increased concentration of pollutants and the lack of proper ventilation system make problems such as the headaches, dizziness, drowsiness and irritation of eyes which are known as the sick building syndrome (SBS). According to the reports by Noyesh [2], approximately 30% of American workers are faced with sick building syndrome and makes about 90 billion dollars loss due to these workers' reduced efficiency.

LITRATURE REVIEW

Many numerical and empirical studies have been conducted on natural displacement flow. Empirical works are important in terms of validating numerical works. A valid numerical work, in spite of fewer costs, can also present more comprehensive information, compared to empirical methods. In the following, numerical and empirical studies conducted on natural flow displacement are discussed.

Empirical Researches

During the last three decades, many empirical studies have been performed on natural flow displacement. For the first time, Elder [5] investigated turbulent in chamber. Later, it was investigated by Schmid and Giel [6]. In these experiments, water has been used instead air and turbulent values have been not measured in the experiments.

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Cheesewright [7] examined average speed, core temperature and turbulent fluctuations in a chamber containing air with temperature difference in walls. Rayleigh number of the chamber flow was about 10^{10} and aspect ratio of the chamber was 5:1. DafaAla and Bets [8] empirically investigated natural flow displacement in a long chamber with aspect ratio of $8.3*10^5$ (computed based on width). In this study, they employed laser speed measurement to measure speed and speed fluctuations as well as thermocouple to measure temperature and its fluctuations.

Numerical Studies

Henkes et al. [10], Lon Khorst [11], Chen [12], and Hanjalic et al. [14] numerically simulated natural flow displacement within a chamber containing air. Henkes et al. [10] employed standard k-ε model and several low raynolds k-ε models to simulate air flow in a square chamber with warm walls with Rayleigh number of 10^{14}. The obtained simulation results indicated that low raynolds k-ε models present more exact answers compared to standard k-ε model to transfer heat from walls.

Lon Khorst [11] used standard k-ε model with wall functions to simulate air flow in a room with radiator. They used wall functions to compute ε and k but not to compute speed and temperature. In their study, Rayleigh number of the chamber was about $3*10^{10}$. Their model had a good prediction of average flow and was consistent with laboratory results; however, it was weak in turbulence modeling. Chen [12] applied various Reynolds stress models (RSM) to compute obligatory natural displacement of the room. The modeling results showed that various RSM methods have identical efficiency in air flow simulation. The results obtained from Chen's modeling were consistent with the average flow values obtained from empirical measurements; however, turbulence values had not been well predicted. Hanjalic et al. [14] used three-equation models of $k-\varepsilon-\overline{\theta}^2$, four-equation model of $V_1-\varepsilon-\overline{\theta}^2-\varepsilon\theta$ and modified LRN model to compute air flow in various empty buildings and partioned buildings. In their study, Rayleigh model was about 10^{10}-10^{12}. This number was consistent with Rayleigh number in real interior spaces. The results of average temprature and speed obtained from the model was also consistent with empirical values.

Mathematical Modelling of Indoor Air Flow

Various scientific communities have widely developed the theory governing transfer phenomena. Applying principles of mass, energy and momentum, mathematical description of governing equations are obtained. Indoor transfer phenomena are described by the following partial differential equations:

- Continuity equation
- Momentum equation
- Energy equation
- Particles' concentration equation

Each of the above equations includes a diffusion part and a displacement part which indicates two important transfer mechanisms, i.e. diffusion and displacement. Diffusion of momentum, energy and mass are resulted by molecular interaction. However, displacement of mass, heat and momentum are due to indoor air flow. The two first equations are used to compute air flow and known as Navier-Stokes equations. The full form of Navier-Stokes equations has not been analytically solved and they can be analytically solved only by considering simple geometry and simplifier assumptions. Most of engineering problems such as indoor air flow are turbulent and have a complex geometry. Therefore, there is no analytical solution for them. The models which are widely used to simulate the behavior of building are as following:

- Building energy modeling
- Comfort conditions modeling
- Indoor air quality modeling

Building Energy Modeling

To design air conditioning equipments, engineers should be able to hourly have the rate of energy required by building. On the other hand, annual energy consumption of building should be determined to reach an optimal design.

The first methods used to model building include a series of simplified equations of energy conservation law. To solve these equations, it was necessary to solve many inputs. These models were known as manual methods. Later on, more advanced models such as transfer function method (TFM) were developed to compute thermal loads of building.

Today, as a result of developing computational and analytical methods and enhancing computers' power, more advanced methods have been developed to simulate energy within building. These simulations are usually based on micro-models and numerical computations. Some of these models are able to consider and simulate comfort conditions as well as indoor air quality as well. The most known computer programs for energy simulation in building are as following:

- DOE-2
- ESP-r
- BLAST
- TRANE/TRACE

Comfort Conditions Modeling

One of the most important tasks of building is to create a comfortable environment within building during all times of a year. During several years, controlling climatic parameters, human have attempted to remove dissatisfactions and annoying factors of environment. For primary human, comfort conditions involve not freezing; however, today, environment comfort is used rather thermal comfort.

During the recent years, many efforts have been done to formulize comfort conditions. Comfort equations of Fanger are the most famous method to estimate indoor comfort. Up to now, a large number of standards have been developed to estimate comfort conditions in ISO and ASHRAE institutes.

Indoor Air Quality Modeling

Air quality models are used to predict the distribution of pollutants' thickness in stable and unstable conditions. Nowadays, modeling is the most important instrument of researchers and engineers to investigate indoor air flow pattern and evaluate the efficiency of air condition systems.

In spite of the fact that designers, architects and researchers consider modeling as a powerful instrument to achieve desirable indoor air quality, many works have been performed to validate these models. However, computer models will de so developed in a near future that can be used for routine design and performance.

Microscopic models: many microscopic models which use mass balance equations have been developed to predict the behavior of pollutants. In these models, production and omission of indoor pollutants are mathematically described by mass balance equation.

Particles' accumulation rate= (the rate of changes due to indoor pollutants) + (the rate of changes due to entering outside air)-(the rate of changes due to exiting air)-(the rate of changes due to omitting pollutants)

In the above mass balance equation, all the mentioned parameters such as the rate of ventilation, production and omission of pollutants should be measured and it is usually a difficult work to do. In these models, a room is considered as an area and no local change or particle distribution is seen in the room. In microscopic methods, air flow conditions are not considered as the model's parameters. One-area methods do not usually lead to accurate answers when pollution resources have not evenly distributed within the room. For such conditions, multi-area conditions are used such that the above mass balance equation is applied on each of the areas.

These models consider only mass concentration of particles and show surface mass transfer phenomena in volume. These models are adequate to consider most of indoor air quality. For example, particles' mass transfer, particles' deposition and particles' chemical interaction are not observed in these models. However, they do not provide any information about spatial distribution of particles. To consider particles' distribution and enter air flow parameters, microscopic models should be used. Computational fluid dynamic (CFD) is a powerful instrument to simulate microscopic indoor air quality.

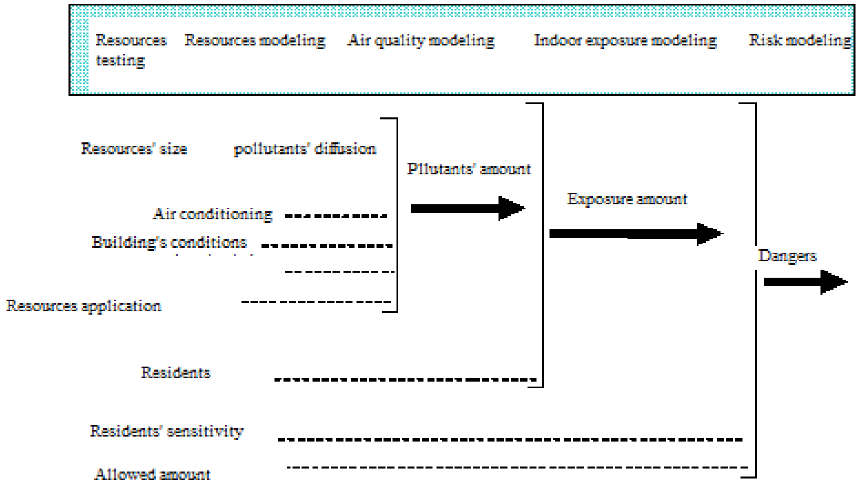

Figure 1. The tasks of indoor air quality models

Table 1. Air quality models classification

General objectives	Model
Estimating residents' exposure	Statistical models
Estimating the effects of pollutant resources	Mass balance models
Estimating the effects of pollutant resources and alternatives of indoor air quality control on individuals' exposure amount	Computational fluid dynamic (CFD)

Mass Balance Models

As stated earlier, mass balance models investigate the effects of pollution production resources on indoor pollutants distribution. These models can be used for one or several parts of a building. In one-part models, desired building is considered as an area while in multi-area models, building is divided into several continuous areas. The mass balance equation of a room is as following:

$$V_i \frac{dC_i}{dt} = C_{iIN} Q_{iIN} - C_{iOUT} Q_{iOUT} + R_i - S_i \tag{2}$$

Where:
V_i : the volume of the room
C_i: the concentration of pollutant in the room
C_{iIN}: the concentration of pollutant entered to the room
Q_{iIN}: the discharge of the entered air
C_{iOUT}: the concentration of pollutant existed from the room
Q_{iOUT}: the discharge of the air existed from the room
R_i : the resource of pollution produced in the room
S_i : the well for the amount of pollution omitted in the room
i: the investigated room

The phrases pertained to resource and well may enter a series of additional differentia equations into equations' class. If indoor air has been well mixed, the output concentration of the room will be equal to the concentration of the room. Total equation for mass balance of the room (i) in a building with N areas is as following:

$$V_i \frac{dC_i}{dt} = C_a Pt_a Q_{ai} + C_h Q_{h,i} + \sum_{i=1\& j\neq N}^{N} C_j Q_{j,i} - C_i Q_{i,a} - C_i Q_{i,h} - \sum_{i=1\& j\neq N}^{N} C_i Q_{i,j} + R_i - S_i \tag{3}$$

Where:
C_a: the concentration of indoor particles
Pt_a: the coefficient of particles' penetration from outside of the building to inside the building
Q_{ai}: the discharge of outside air mass directly entered
C_h: the concentration of pollutant in ventilation system
$Q_{h,i}$: the mass discharge of air entered from ventilation system to the room
C_j: the concentration of pollutant in the room

$Q_{i,h,j}$: the discharge of air entered from ventilation system to the room

$Q_{i,j}$:the discharge of air entered from the room (*i*) to the room (*j*)

For each of the building's area, an equation similar to equation (3) is written. Then, a class of equations is obtained which should be simultaneously solved. If the values of resources, well, and input and output discharges are constant in time interval of t_i to t, the equation will be analytically solved.

$$C_i = C_i(t_0)e^{-L(t-t_0)} + \frac{P_i}{L_i}(1-e^{-L(t-t_0)}) \tag{4}$$

Where C_i (t_0) indicates pollution concentration in the room at time. L_i and P_i are computed as following:

$$L_i = \frac{Q_{i,a} + Q_{i,h} + \sum_{j=1, j\neq i}^{N} Q_{i,j}}{V_i} \tag{5}$$

$$p_i = \frac{1}{V_i}\left[\sum_{j=1, j\neq i}^{N} Q_{j,i}C_j(t) + R_i - S_i + Q_{a,i}C_a Pt_a + Q_{h,i}C_h\right] \tag{5}$$

Even distribution of pollution concentration is the main assumption of mass balance-based models. Even concentration conditions are valid in case of meeting the following items:

- Time scale of computations is greater than minute rank.
- Pollution concentration is not taken into consideration near large resources.
- There is no disturbance in regions under investigation.

RESULTS

Here, we present the results of numerical simulations for two different rooms. The simulations are done for parameters such as the temperature, speed, humidity, radiation temperature, and distribution of carbon monoxide and nitrogen dioxide pollutants. Figure (2) shows the model of room (1). The dimensions of this room are 4.7m * 3m* 2.75m and a window with the dimensions of 1.83m * 1.44m is in the northern side and a wall cupboard built in the eastern side of room. The window boundary conditions are considered in a way that the required fresh air is supplied by its entrance. According to the calculations, the rate of CO emitted from the fireplace is considered equal to 7 ppm and the amount of NO_2 equal to 0.025 ppm. In order to apply the appropriate boundary conditions for heating, the room heating load is measured by Carrier software and its results are presented in figure (3). As shown, the heating load is equal to 8527 Btu/hr which is considered as the thermal power of fireplace. The outer temperature is equal to -2.5 °C.

Figures (5) to (8) respectively show the distribution of temperature values, radiation temperature, relative humidity and air speed in sheet x=3.2. Using the above mentioned values and considering the coverage factor (clo) equal to 0.6 and the metabolic rate of met 1, the PMV index is calculated and shown in Figure (9). As shown, almost a half of room is in comfort. The figures (10) and (11) show the distribution of pollutants including CO and NO_2 in the sheet of x=3.2. As shown, the maximum amount is related to the emitted steam, and the concentration is lower in the other spaces of room.

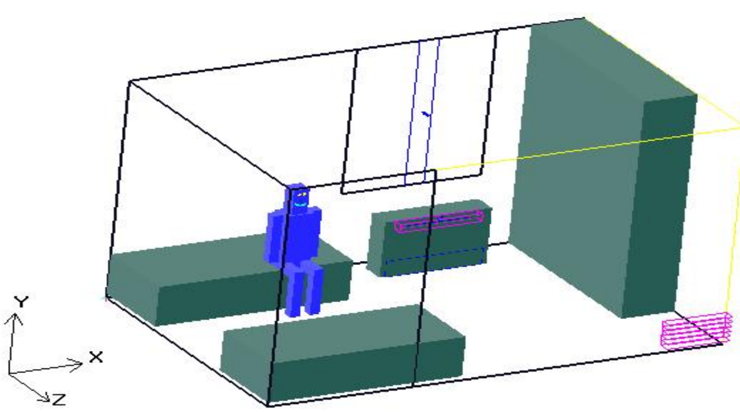

Figure 2. Model of room (1)

Space Design Load Summary for Heating & Coling Loads

Project Name:
Prepared by:

TABLE 1.7.A. COMPONENT LOADS FOR SPACE " F1U2bedroom " IN ZONE " Zone 1 "						
	DESIGN COOLING			DESIGN HEATING		
	COOLING DATA AT Jul 1900 COOLING OA DB / WB 91.5 °F / 72.0 °F OCCUPIED T-STAT 78.0 °F			HEATING DATA AT DES HTG HEATING OA DB / WB 18.0 °F / 17.2 °F OCCUPIED T-STAT 76.0 °F		
SPACE LOADS	Details	Sensible (BTU/hr)	Latent (BTU/hr)	Details	Sensible (BTU/hr)	Latent (BTU/hr)
Window & Skylight Solar Loads	28 ft²	508	-	28 ft²	-	-
Wall Transmission	233 ft²	1453	-	233 ft²	3439	-
Roof Transmission	0 ft²	0	-	0 ft²	0	-
Window Transmission	28 ft²	144	-	28 ft²	737	-
Skylight Transmission	0 ft²	0	-	0 ft²	0	-
Door Loads	0 ft²	0	-	0 ft²	0	-
Floor Transmission	144 ft²	196	-	144 ft²	1083	-
Partitions	24 ft²	59	-	24 ft²	145	-
Ceiling	0 ft²	0	-	0 ft²	0	-
Overhead Lighting	288 W	795	-	0	0	-
Task Lighting	0 W	0	-	0	0	-
Electric Equipment	0 W	0	-	0	0	-
People	2	441	270	0	0	0
Infiltration	-	270	321	-	1155	0
Miscellaneous	-	0	0	-	0	0
Safety Factor	20% / 20%	773	118	30%	1968	0
>> Total Zone Loads	-	4638	709	-	8527	0

TABLE 1.7.B. ENVELOPE LOADS FOR SPACE " F1U2bedroom " IN ZONE " Zone 1 "						
	Area (ft²)	U-Value (BTU/(hr-ft²-°F))	Shade Coeff.	COOLING TRANS (BTU/hr)	COOLING SOLAR (BTU/hr)	HEATING TRANS (BTU/hr)
W EXPOSURE						
WALL	88	0.502	-	1282	-	2573
N EXPOSURE						
WALL	102	0.104	-	108	-	609
WINDOW 1	28	0.450	0.701	144	508	737
S EXPOSURE						
WALL	43	0.104	-	63	-	256

Figure 3. The output of CARRIER for the room (1)

Now, the obtained results of the numerical simulation for two different rooms will be presented. Figures 4 to 7 present the way of distributing values of temperature, radiation temperature, relative humidity, and air speed in the page of X=3.2. Using the above values and considering cover coefficient of CLO (0,6) and metabolic rate (1met), PMV index is computed (figure 10). As observed, half of the room has comfort conditions.

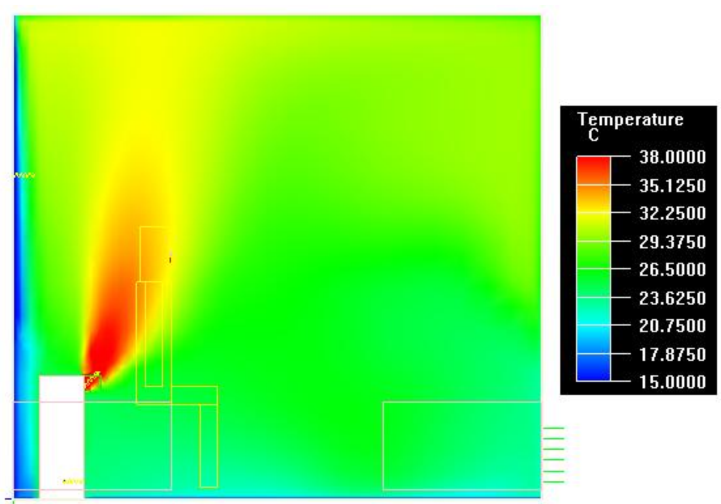

Figure 4. Temperature changes in X=3.2

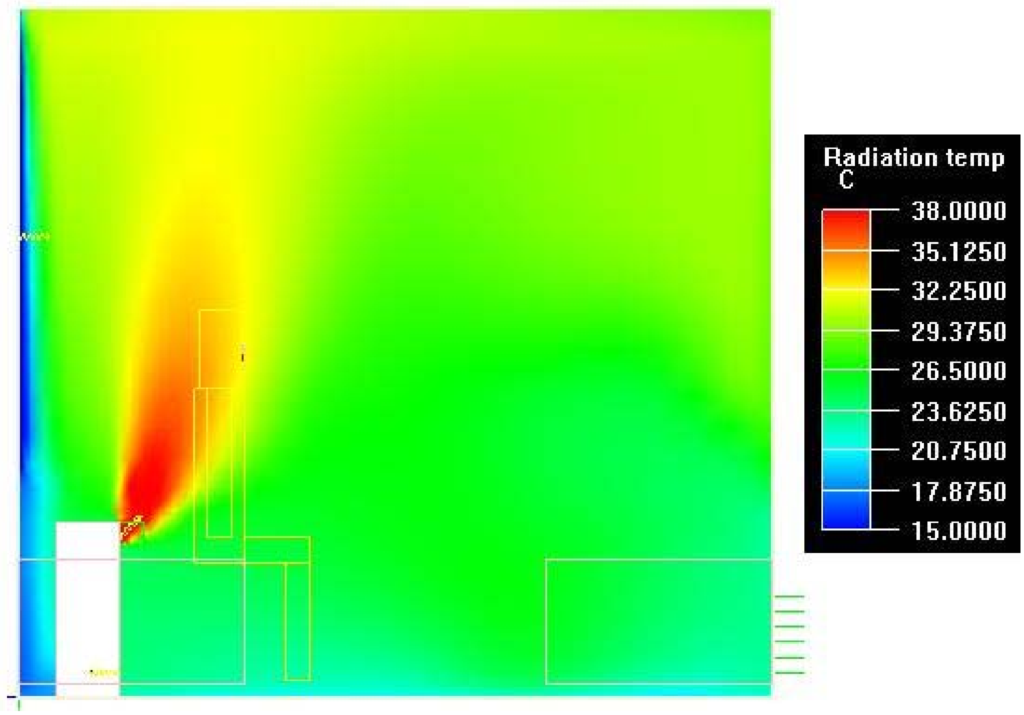

Figure 5. Radiation temperature changes in X=3.2

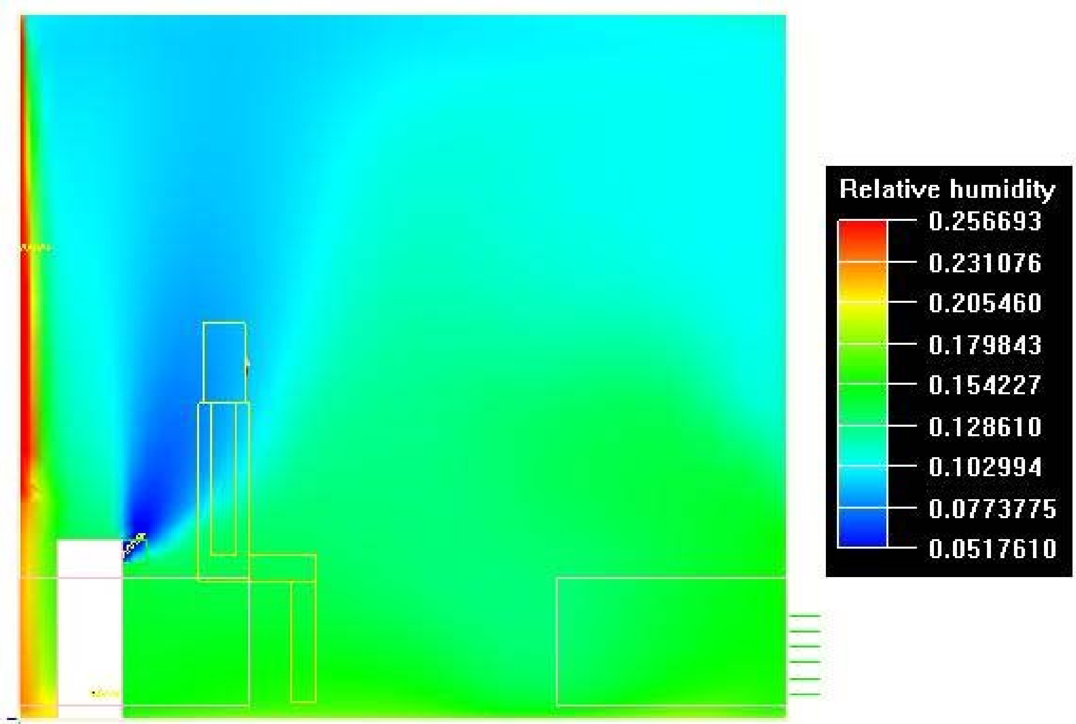

Figure 6. Relative humidity changes in X=3.2

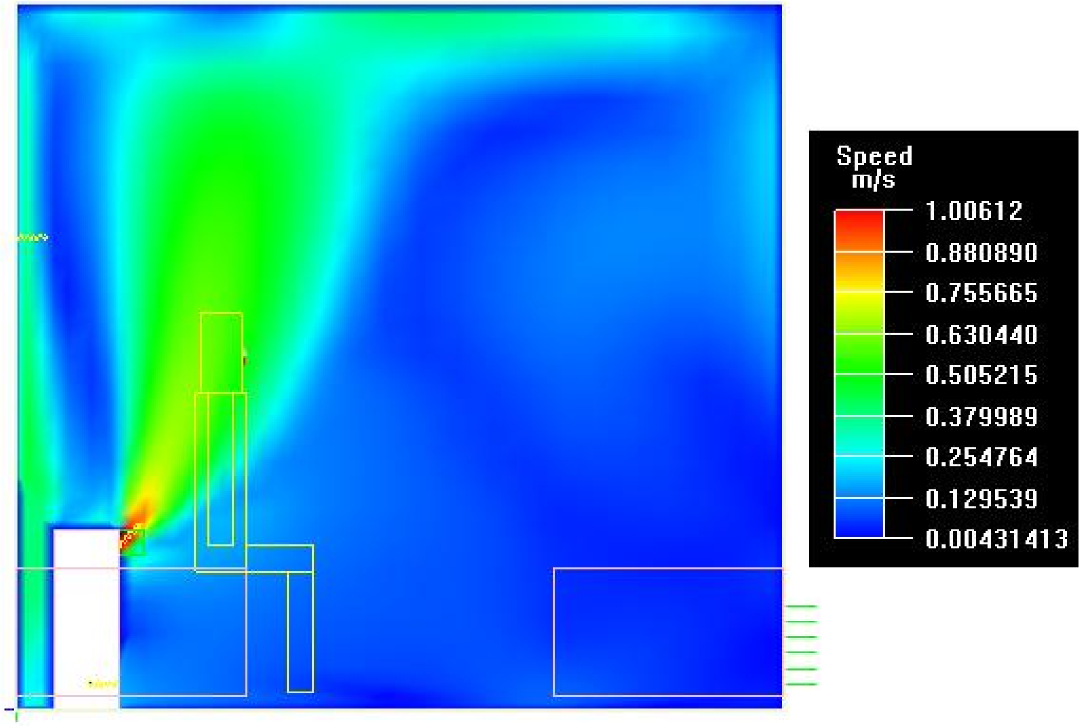

Figure 7. Speed changes in X=3.2

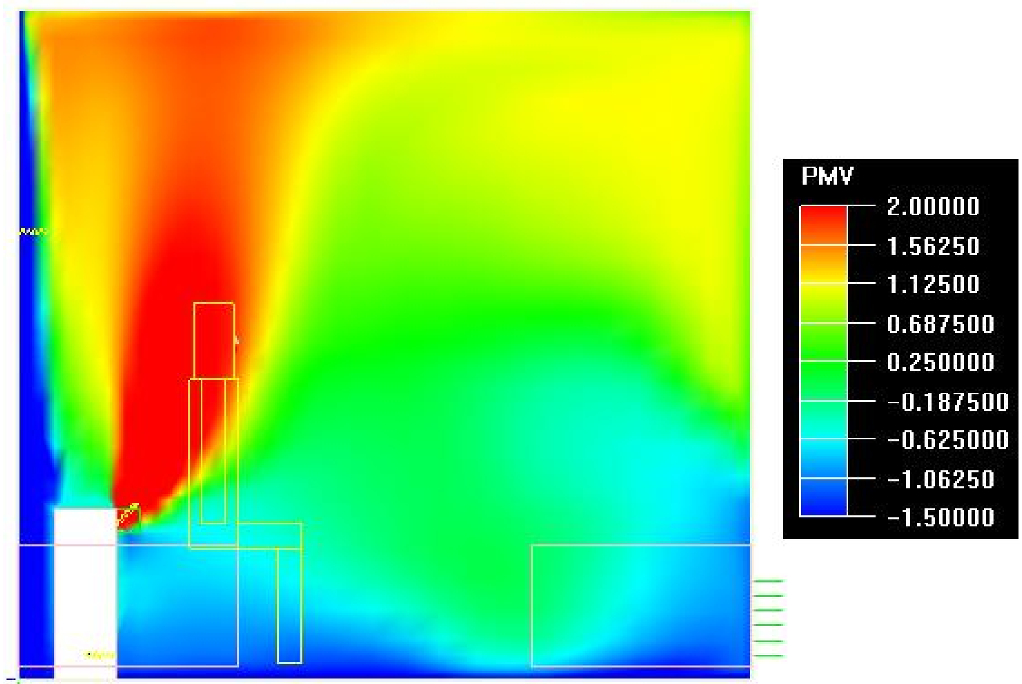

Figure 8. PMV changes in X=3.2

Figures 9 and 10 shows the way of CO and NO_2 distribution in the page of X=3.2. As seen, the maximum value pertains to the fireplace's exit and the concentration is less in other spaces of the room.

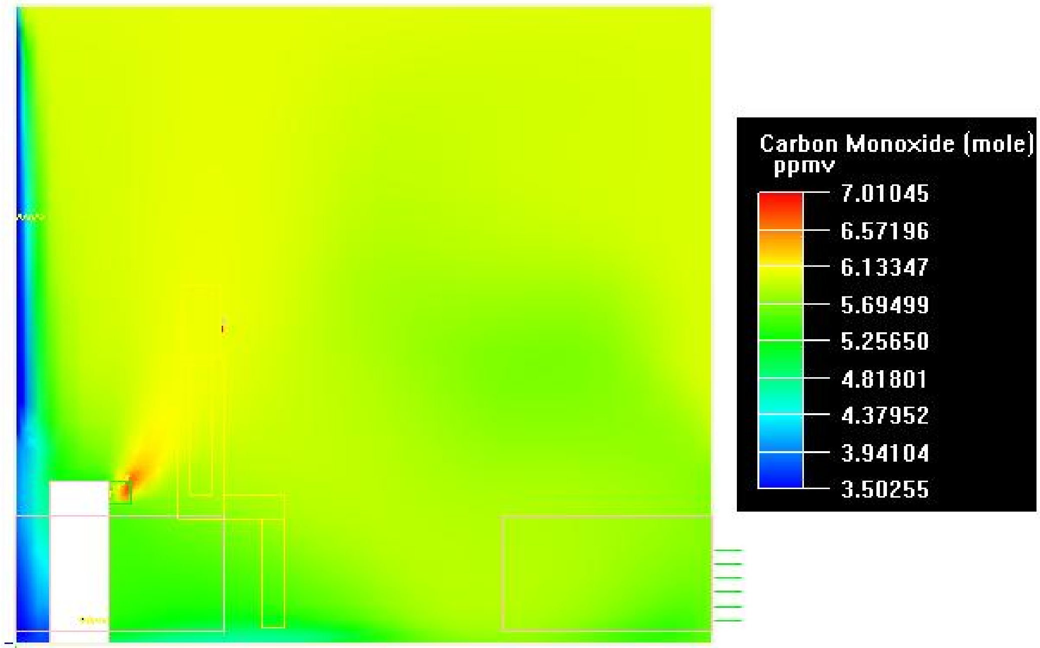

Figure 9. CO concentration changes in X=3.2

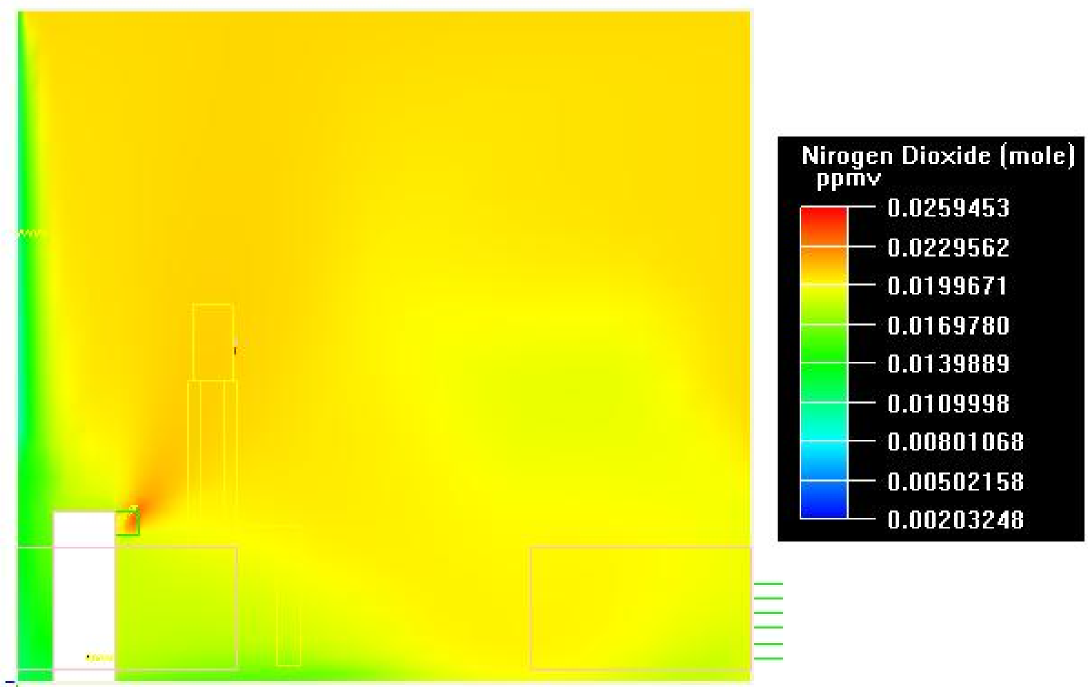

Figure 10. NO_2 concentration changes in X=3.2

Figures 11 to 14 show the distribution profile of temperature, radiation temperature and air speed in the page of z=1.5, respectively. Figure 15 shows the distribution of PMV index in this page. Figures 16 and 17 show the distribution of C and NO_2 in z=1.5.

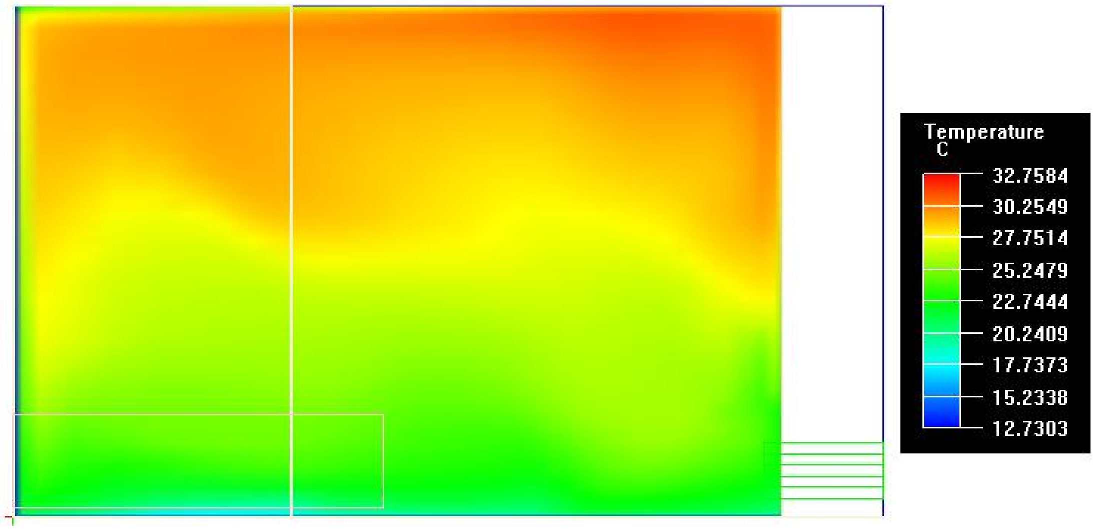

Figure 11. Temperature changes in z=1.5

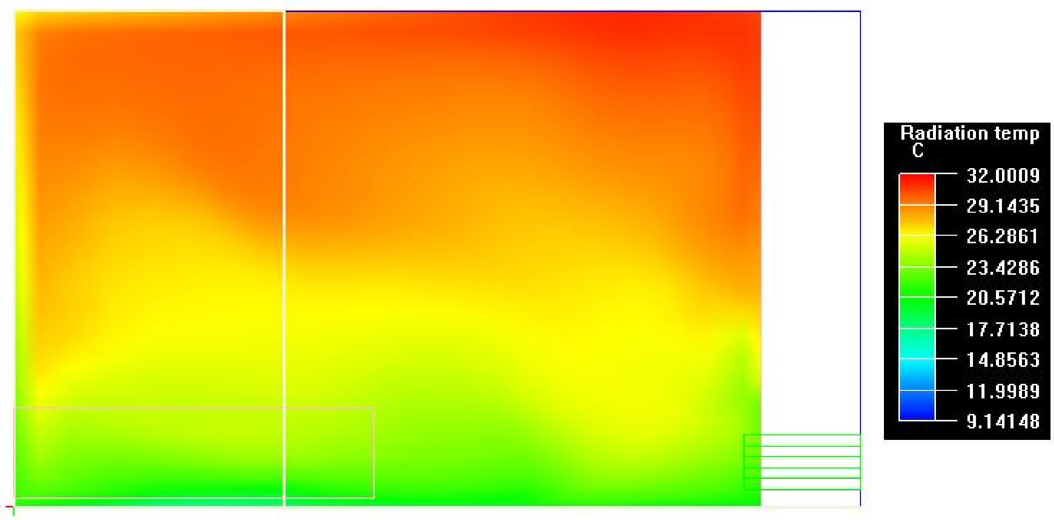

Figure 12. Radiation temperature changes in z=1.5

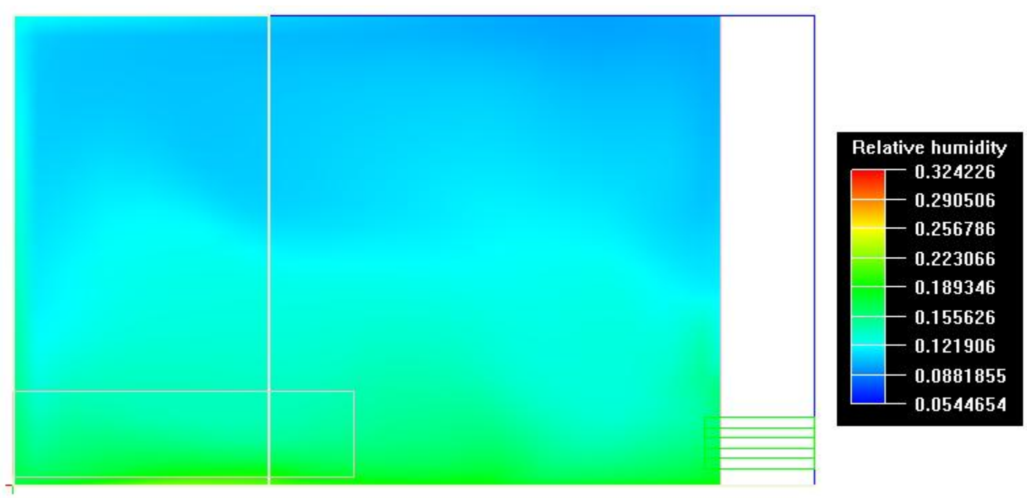

Figure 13. Relative humidity changes in z=1.5

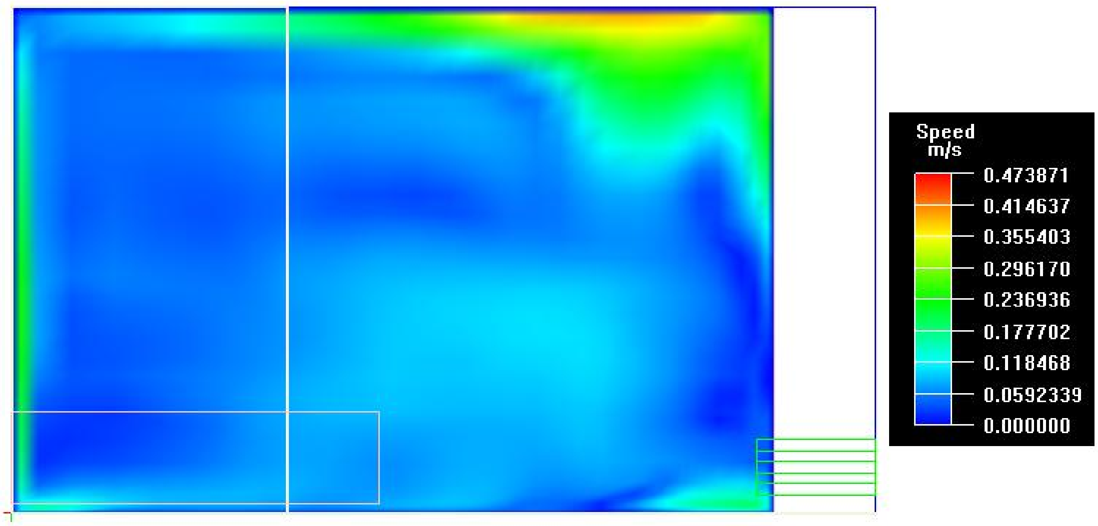

Figure 14. Speed changes in z=1.5

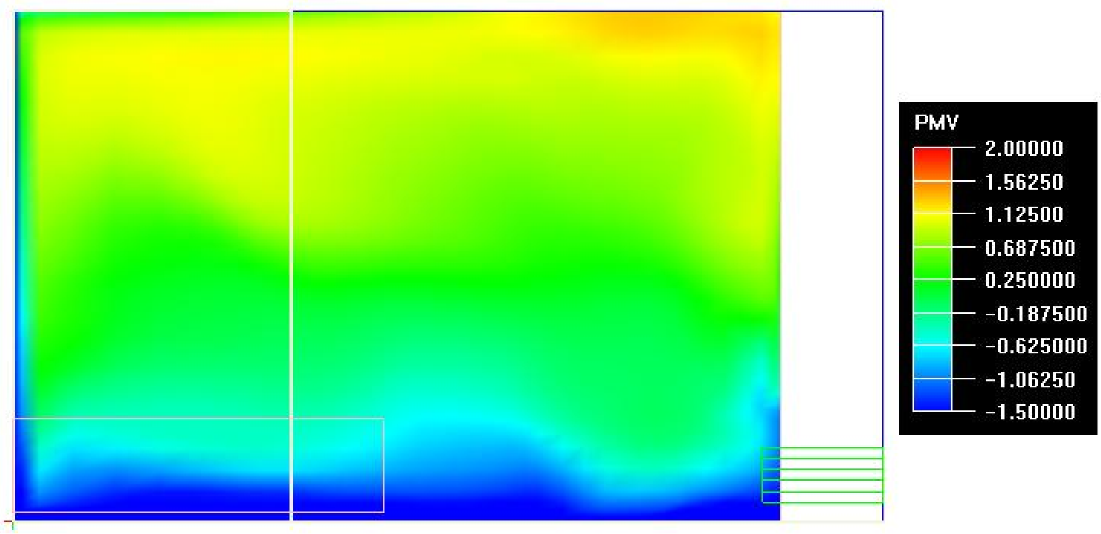

Figure 15. PMV change in z=1.5

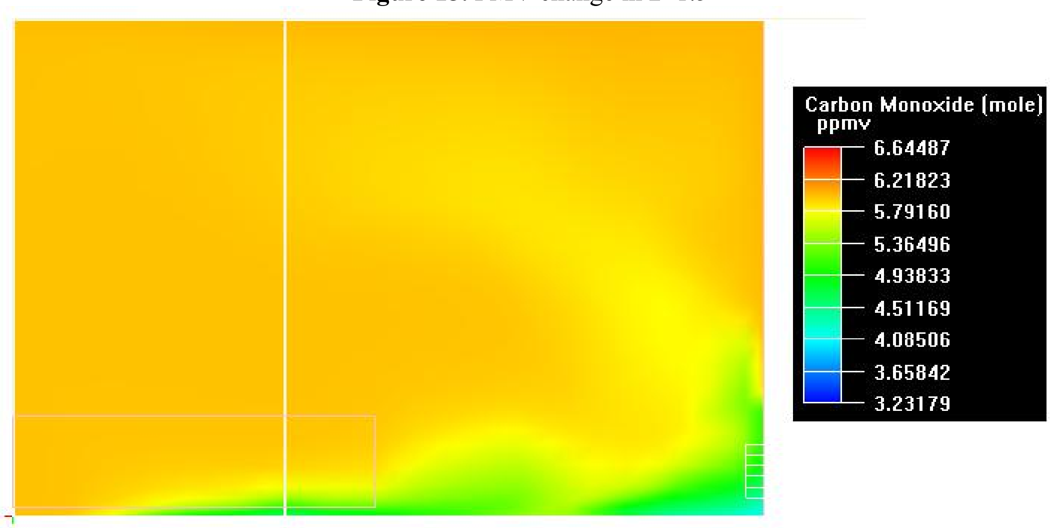

Figure 16. CO changes in z=1.5

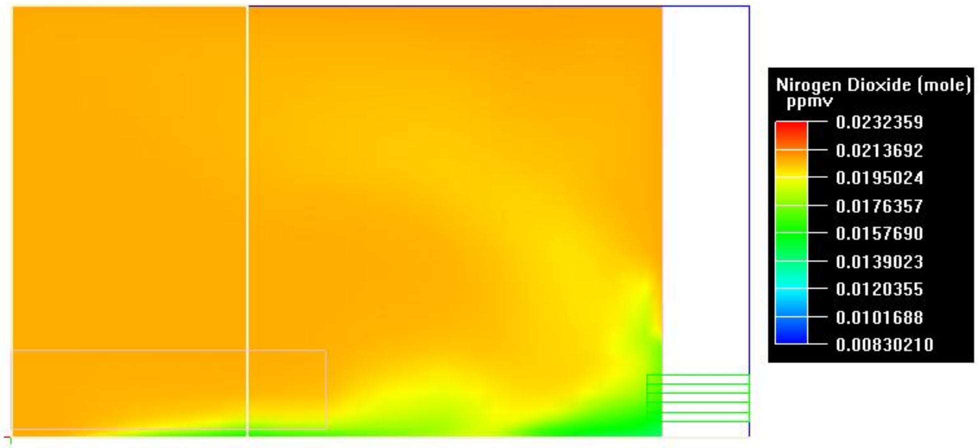

Figure 17. NO_2 changes in z=1.5

Figures 18 to 21 present the distribution of temperature, radiation temperature and air speed in y=17. Figure 22 shows PMV distribution in this page. Figures 23 and 24 present the distribution of CO and NO_2 in y=1.7.

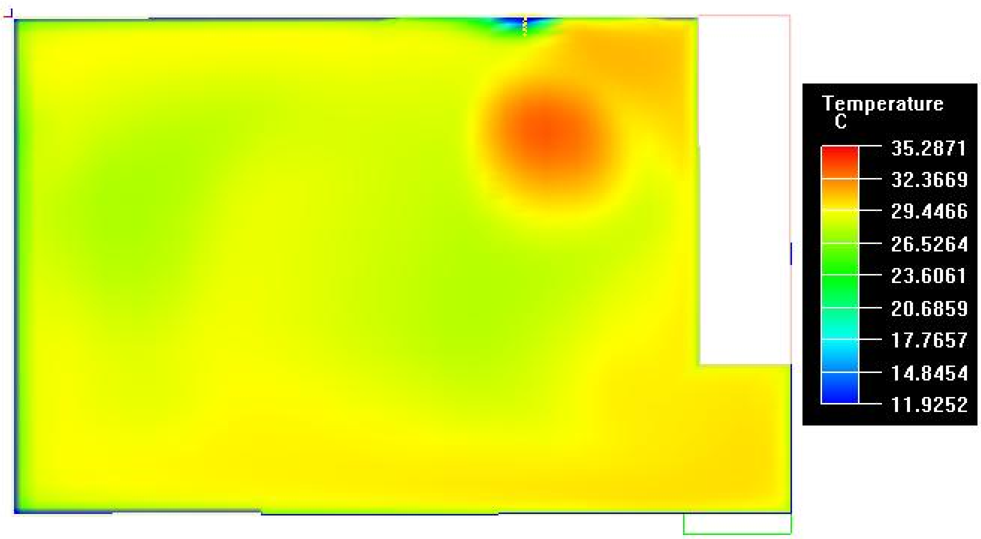

Figure 18. Temperature change in y=1.7

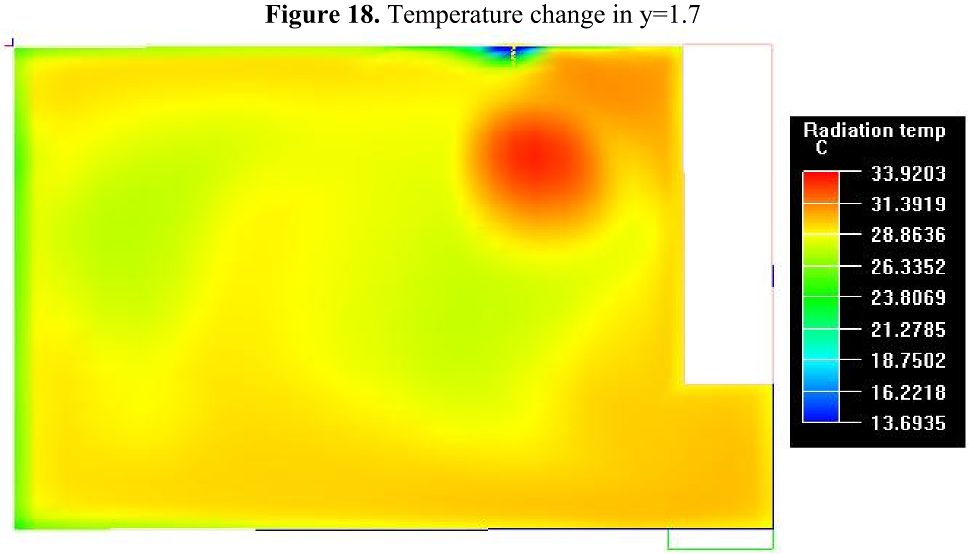

Figure 19. Radiation temperature changes in y=1.7

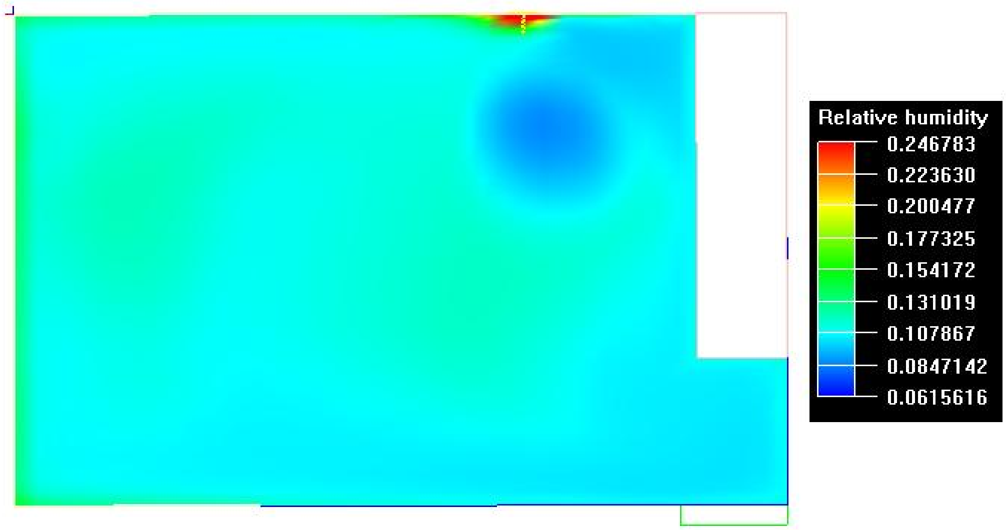

Figure 20. Relative humidity changes in y=1.7

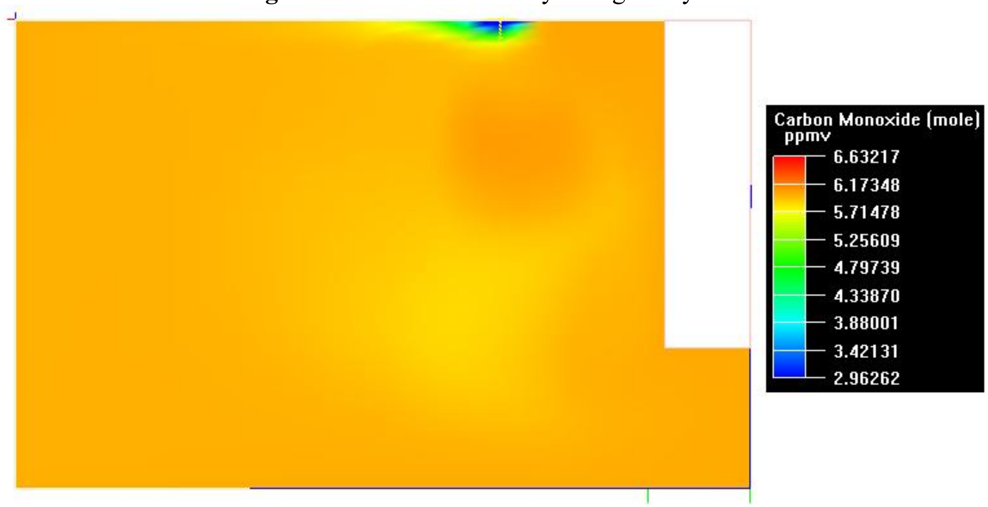

Figure 21. Speed changes in y=1.7

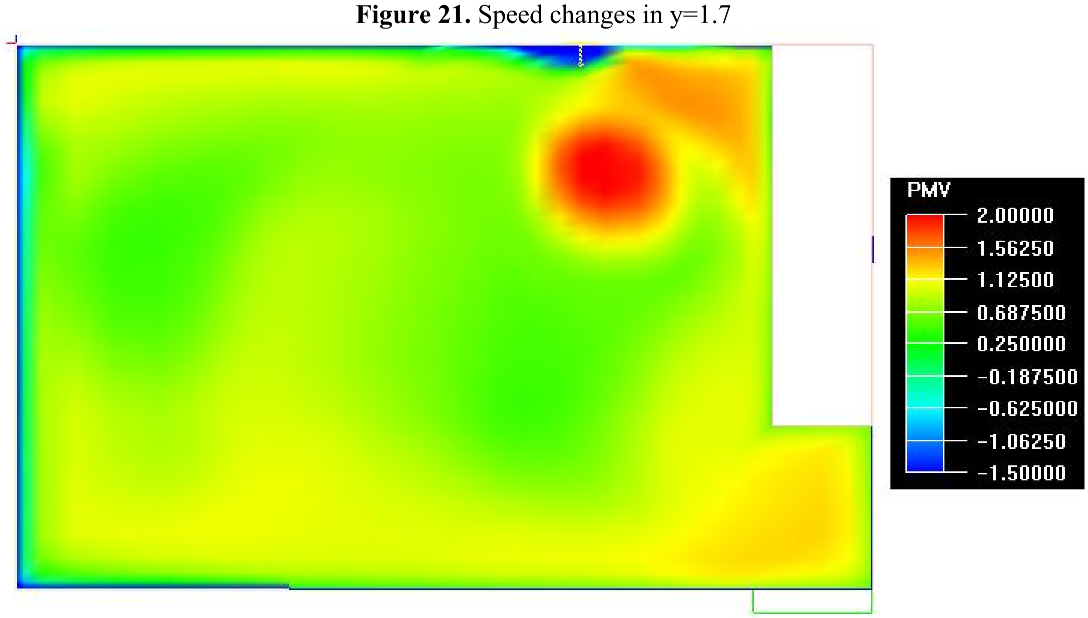

Figure 22. PMV changes in y=1.7

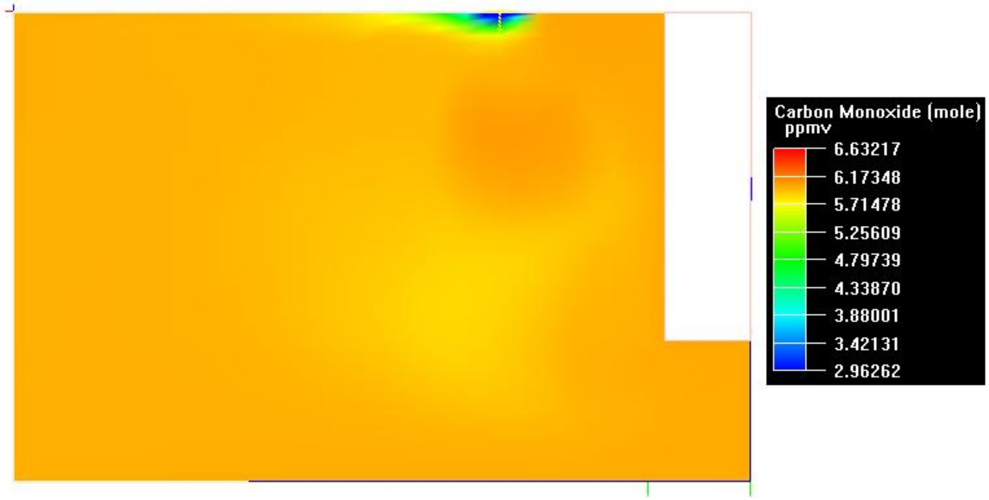

Figure 23. CO changes in y=1.7

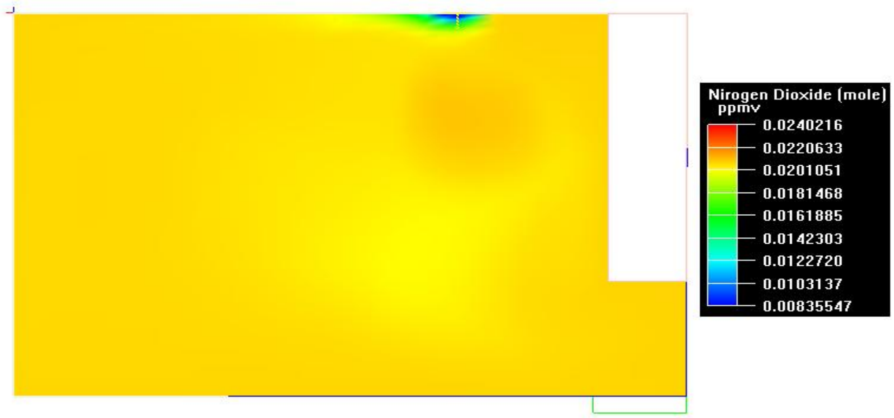

Figure 24. NO_2 changes in y=1.7

Figure 25 shows the model of the room (2). This room has a size of 2.75m✕4.84m✕3m. In this room, there is a window with the size of 1.83m✕ 1.45m in northern side. Just like the room (1), fresh air entrance has been placed on the window. Also, the amount of CO of fireplace's exit has been considered 7 ppm and the amount of NO_2 has been considered 0.025 ppm. Figure 26 shows the results of CARRIER Software in which heating load equals 5919 Btu/hr.

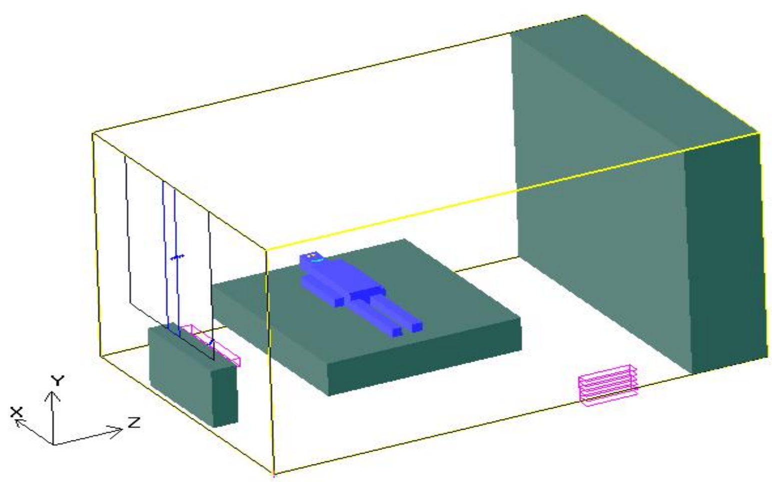

Figure 25. The model of the room (2)

Space Design Load Summary for Heating & Coling Loads

Project Name	05/28/2008
Prepared by: .	12:29È.Ù

TABLE 1.11.A. COMPONENT LOADS FOR SPACE " F1U2Masterbedroom " IN ZONE " Zone 1 "						
	DESIGN COOLING			DESIGN HEATING		
	COOLING DATA AT Jul 1900 COOLING OA DB / WB 91.5 °F / 72.0 °F OCCUPIED T-STAT 78.0 °F			HEATING DATA AT DES HTG HEATING OA DB / WB 18.0 °F / 17.2 °F OCCUPIED T-STAT 76.0 °F		
		Sensible	Latent		Sensible	Latent
SPACE LOADS	Details	(BTU/hr)	(BTU/hr)	Details	(BTU/hr)	(BTU/hr)
Window & Skylight Solar Loads	28 ft²	508	-	28 ft²	-	-
Wall Transmission	201 ft²	443	-	201 ft²	1208	-
Roof Transmission	0 ft²	0	-	0 ft²	0	-
Window Transmission	28 ft²	144	-	28 ft²	737	-
Skylight Transmission	0 ft²	0	-	0 ft²	0	-
Door Loads	0 ft²	0	-	0 ft²	0	-
Floor Transmission	154 ft²	210	-	154 ft²	1158	-
Partitions	35 ft²	102	-	35 ft²	217	-
Ceiling	0 ft²	0	-	0 ft²	0	-
Overhead Lighting	308 W	850	-	0	0	-
Task Lighting	0 W	0	-	0	0	-
Electric Equipment	250 W	768	-	0	0	-
People	2	441	270	0	0	0
Infiltration	-	288	343	-	1235	0
Miscellaneous	-	0	0	-	0	0
Safety Factor	20% / 20%	750	123	30%	1366	0
>> Total Zone Loads	-	4503	735	-	5919	0

TABLE 1.11.B. ENVELOPE LOADS FOR SPACE " F1U2Masterbedroom " IN ZONE " Zone 1 "						
				COOLING	COOLING	HEATING
	Area	U-Value	Shade	TRANS	SOLAR	TRANS
	(ft²)	(BTU/(hr-ft²-°F))	Coeff.	(BTU/hr)	(BTU/hr)	(BTU/hr)
E EXPOSURE						
WALL	142	0.104	-	379	-	850
N EXPOSURE						
WALL	60	0.104	-	63	-	358
WINDOW 1	28	0.450	0.701	144	508	737
WALL	43	0.104	-	63	-	256

Figure 26. The output of CARRIER Software for the room (2)

Figures 27 to 30 present the profile of temperature, radiation temperature, relative humidity, and air speed in X=1.5. Using the above values, PMV index is computed (figure 31). Figure 32 and Figure 33 show CO and NO_2 distribution.

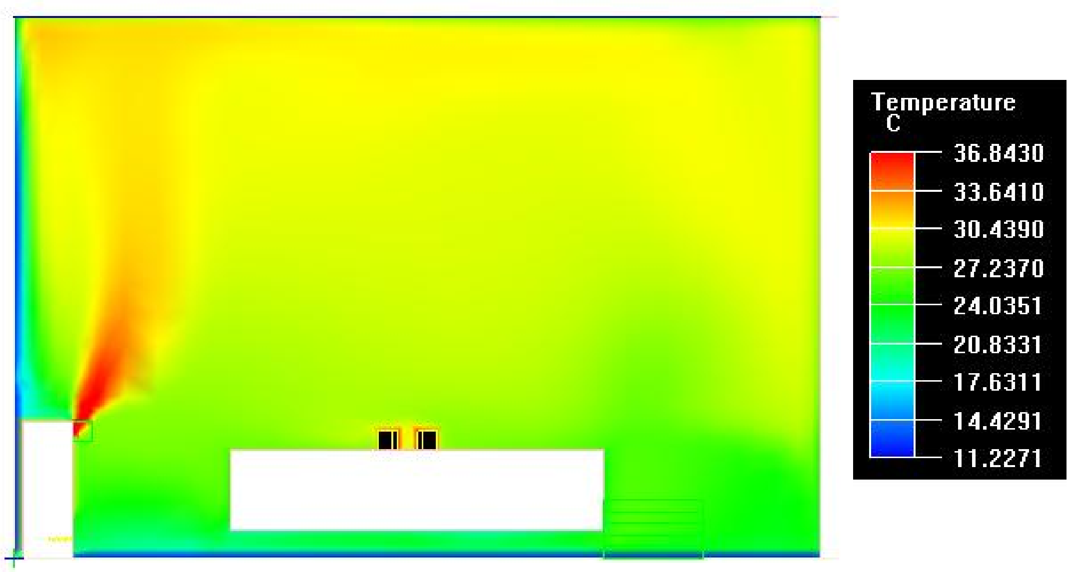

Figure 27. Temprature changes in X=1.5

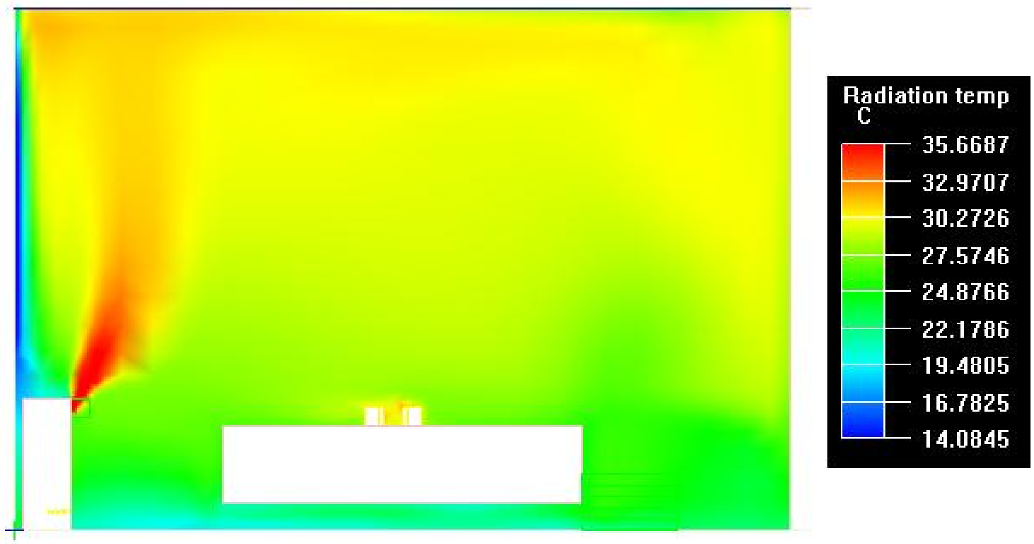

Figure 28. Radiation temprature changes in X=1.5

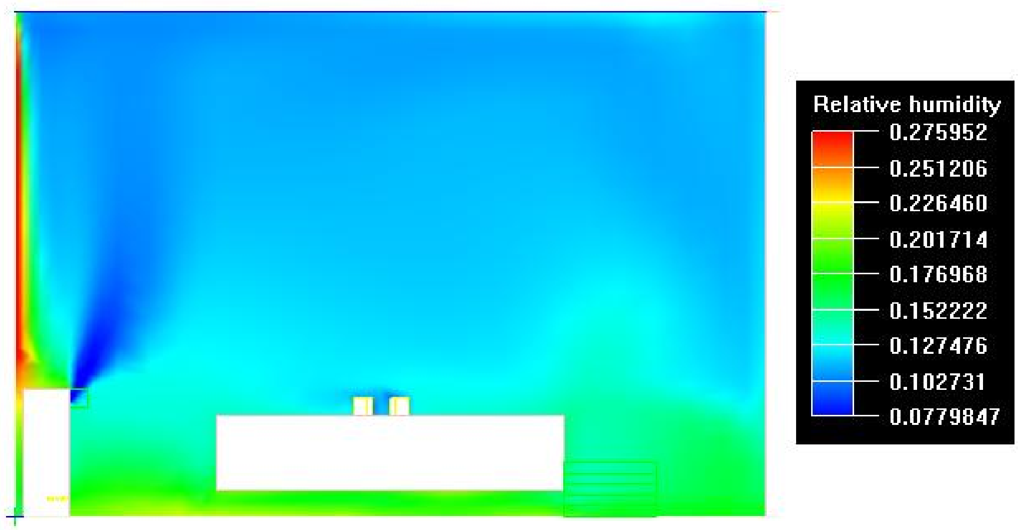

Figure 29. Relative humiditychanges in X=1.5

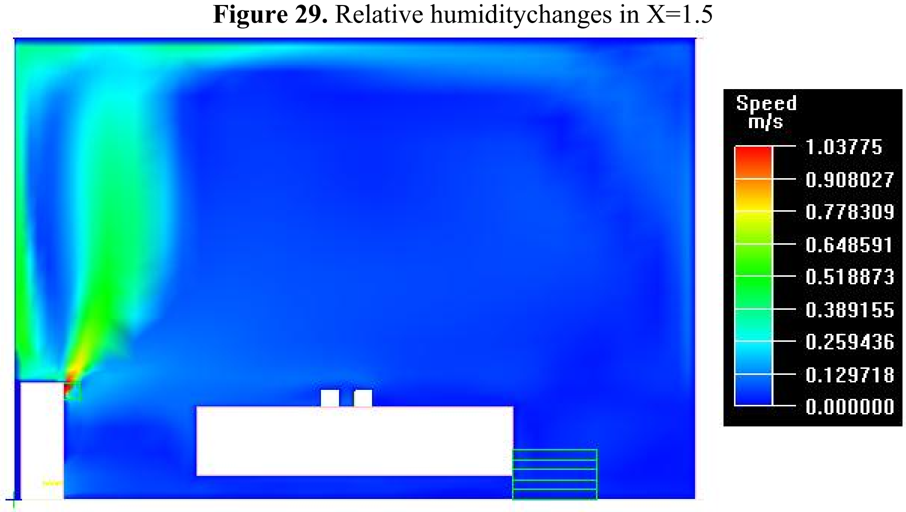

Figure 30. Speed changes in X=1.5

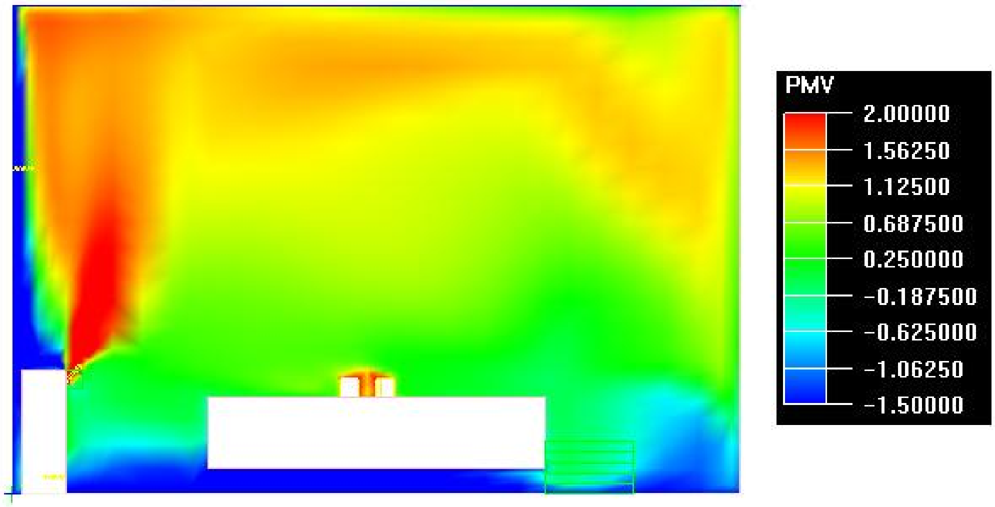

Figure 31. PMV changes in X=1.5

Figure 32. CO concentarion changes in X=1.5

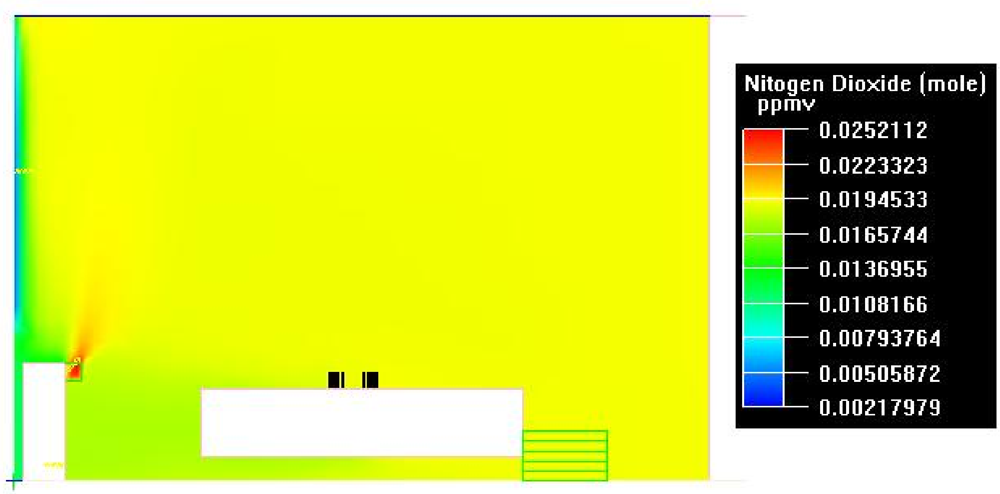

Figure 33. NO_2 concentarion changes in X=1.5

Figures 34 to 37 show the changes of temperature, radiation temperature and air speed in the page of z=2. Figure 38 shows the change of PMV index in this page. Figures 39 and 40 show the distribution of C and NO2 in z=2.

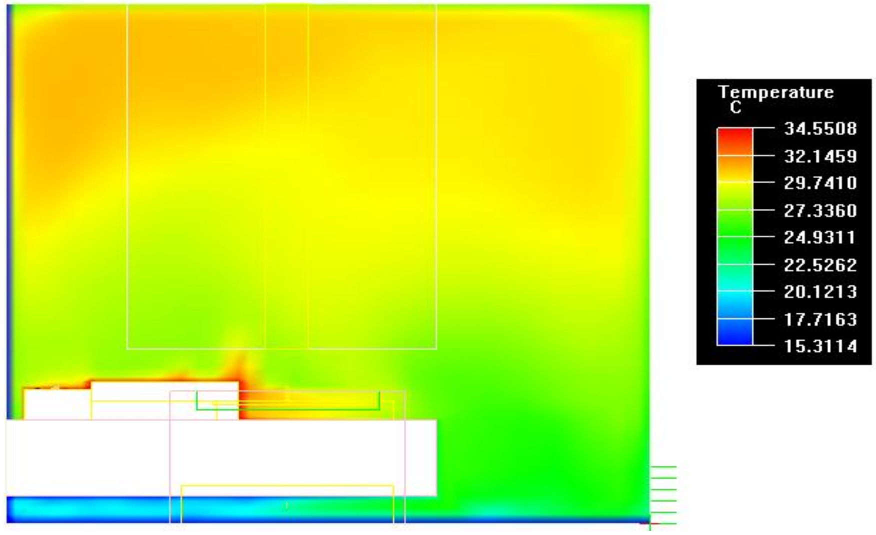

Figure 34. Temperature changes in z=2

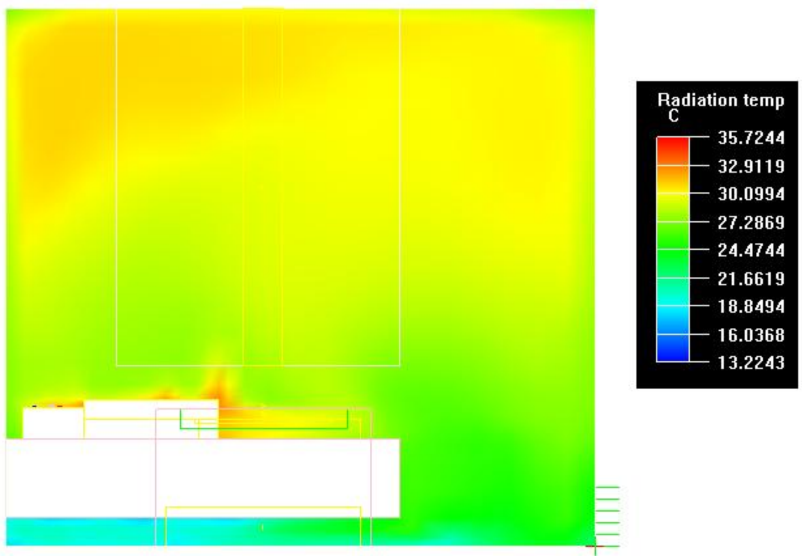

Figure 35. Radiation temperature changes in z=2

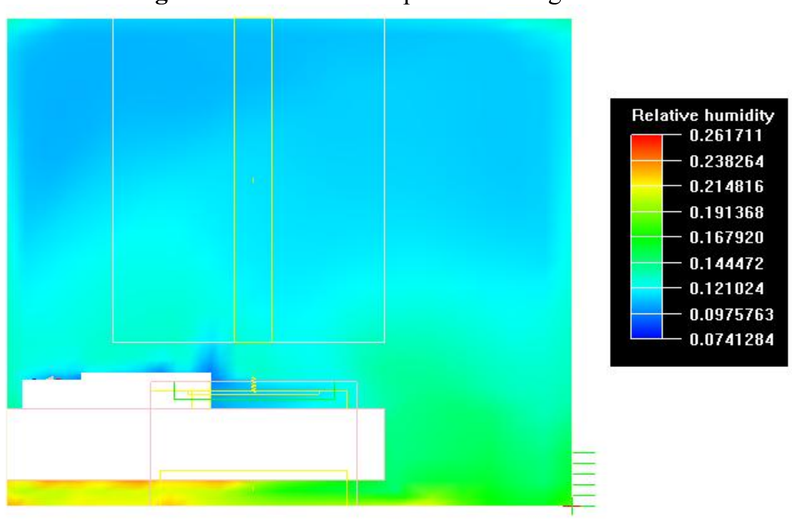

Figure 36. Relative humidity changes in z=2

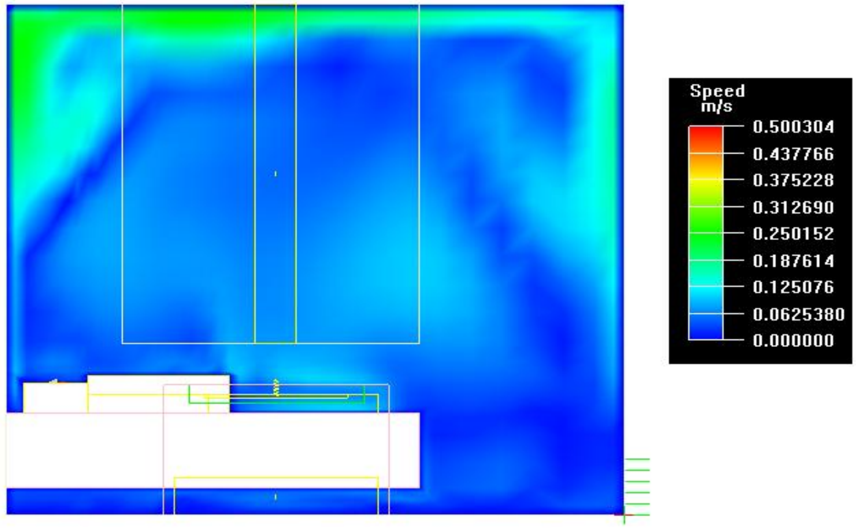

Figure 37. Speed changes in z=2

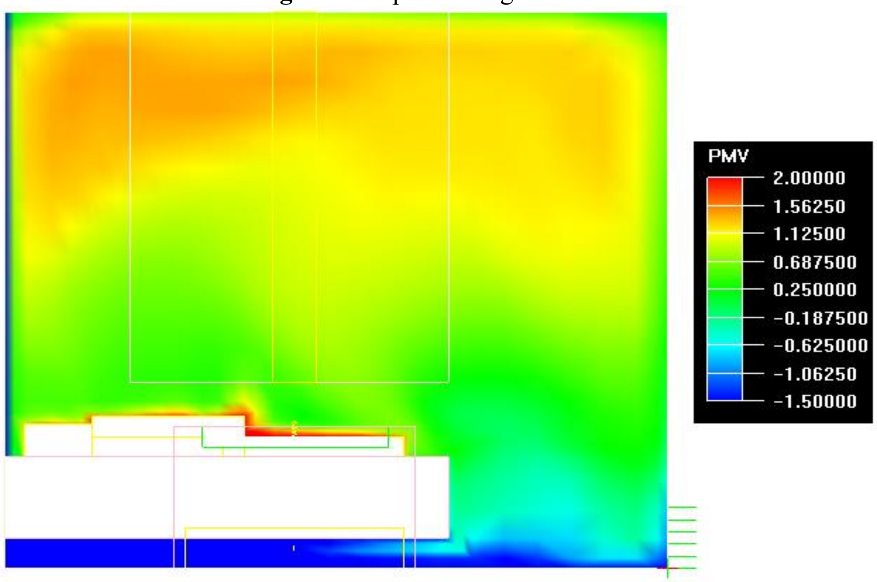

Figure 38. PMV changes in z=2

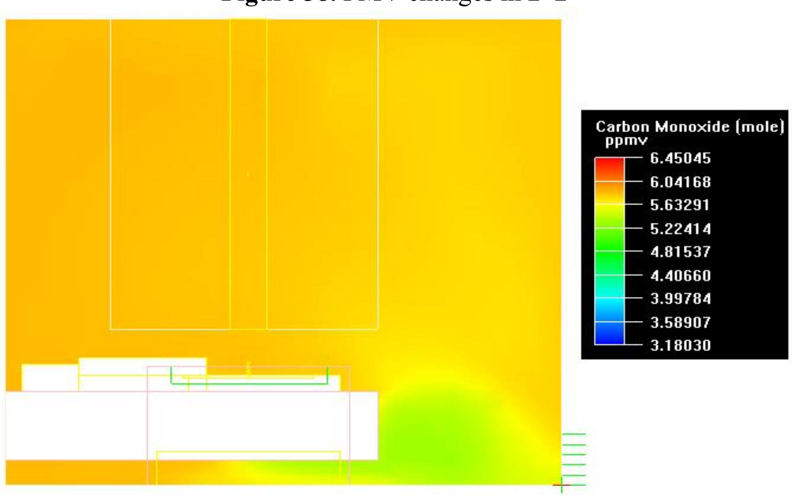

Figure 39. CO concentration changes in z=2

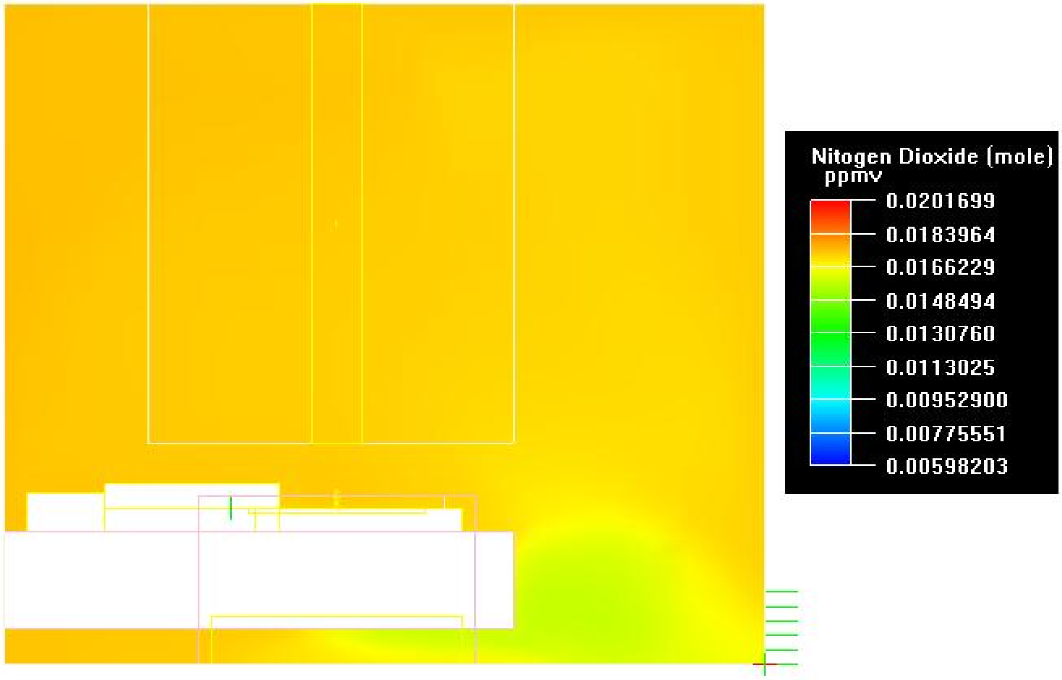

Figure 40. NO_2 concentration changes in z=2

Figures 41 to 44 show the profile of temprature, radiation temprature and speed in y=0.9. also, figure 45 shows PMV index in this page. Figures 46 and 47 present the way of CO and NO_2 distributions.

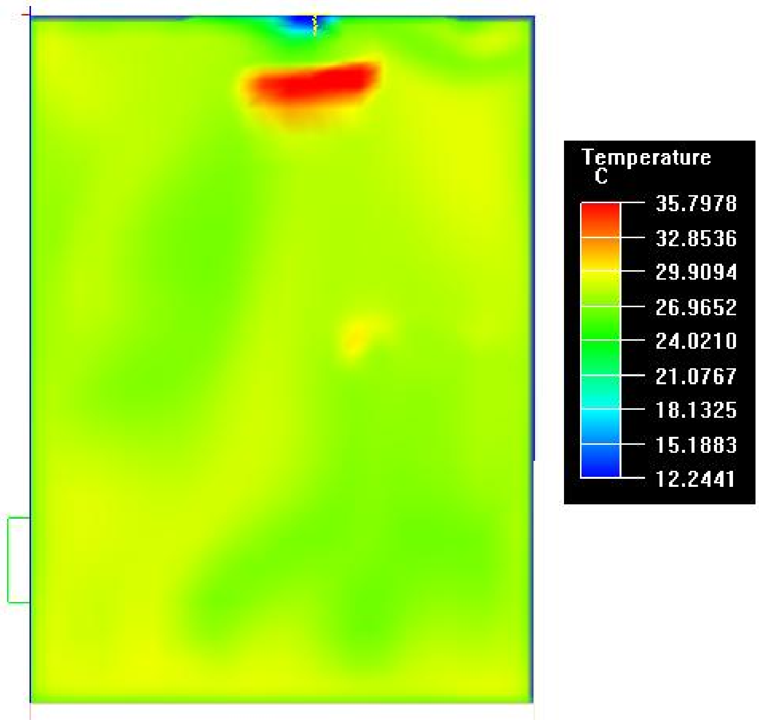

Figure 41. Temprature changes in y=0.9

The profiles of tempreture, radiation tempreture, relative humidity and speed for y= 0.9 are presented in figures 42 to 45. Furthermore, the PMV index of this sheet is shown in figure 46. The figures 47 and 48 show the way of distributing CO and NO2 pollutants.

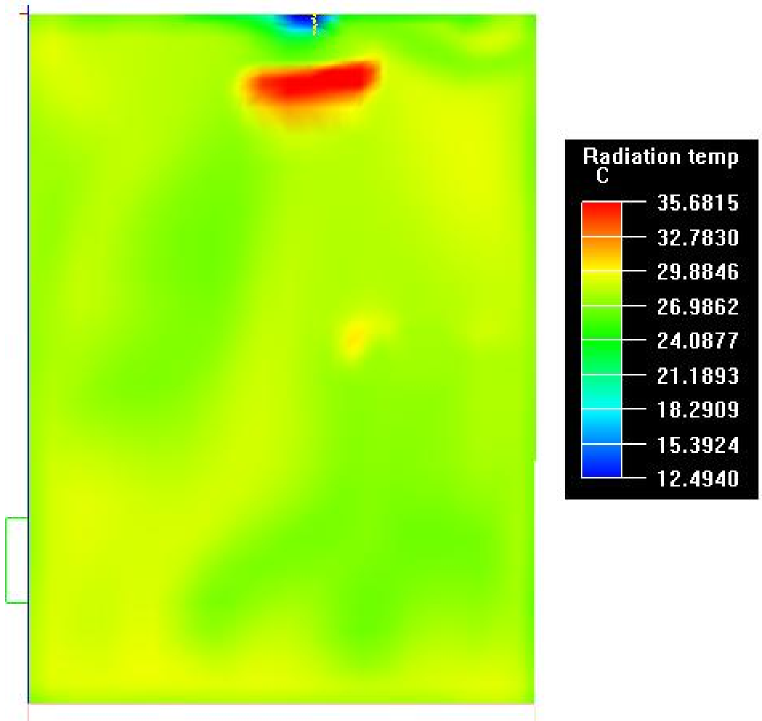

Figure 42. Radiaiton temprature changes in y=0.9

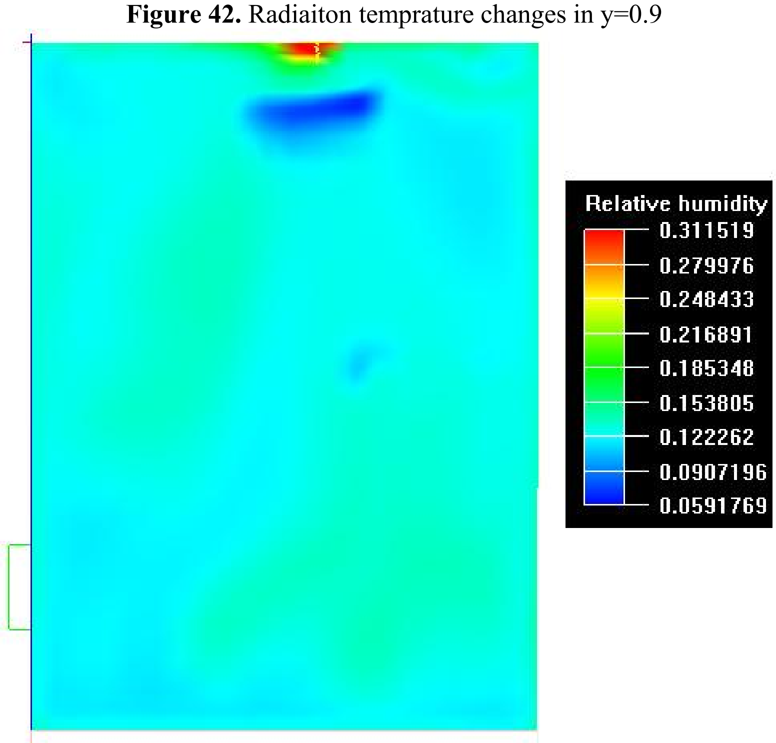

Figure 43. Relative humiditye changes in y=0.9

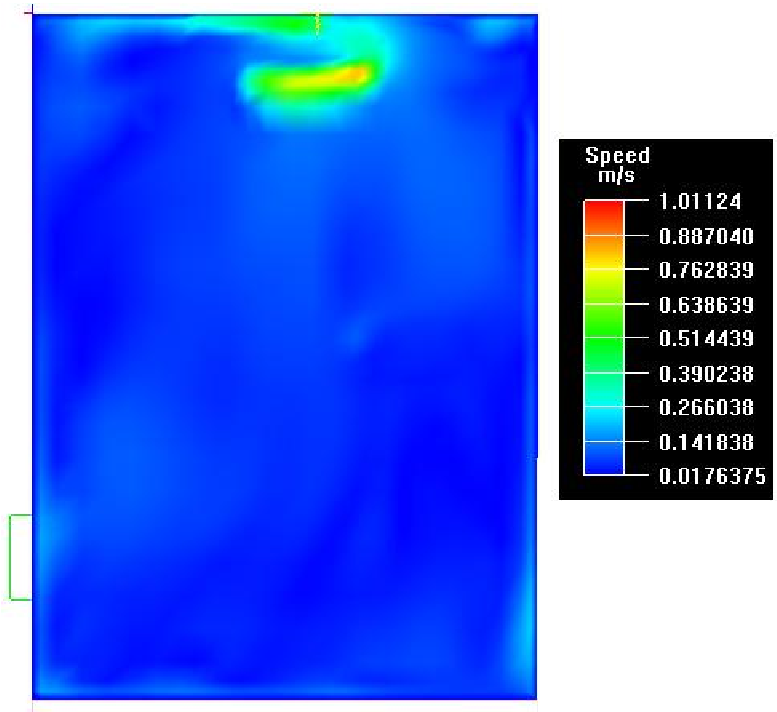

Figure 44. Speed changes in y=0.9

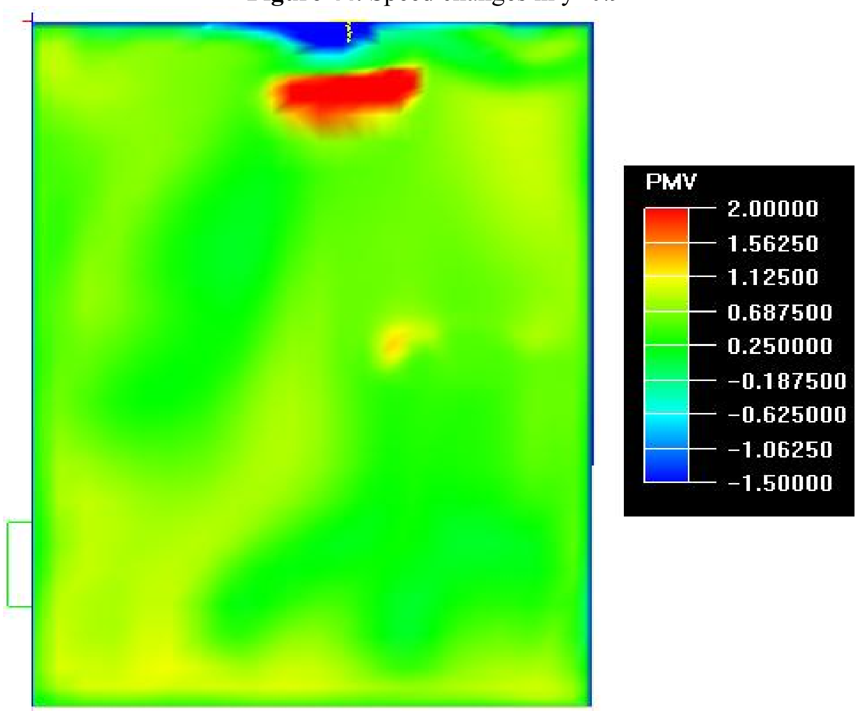

Figure 45. PMV changes in y=0.9

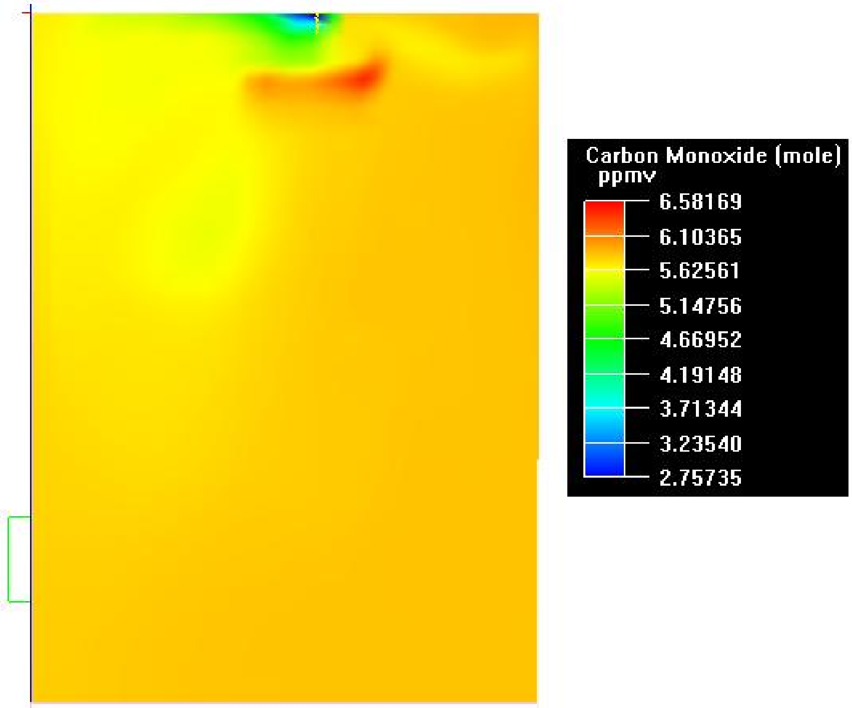

Figure 46. CO concentration changes in y=0.9

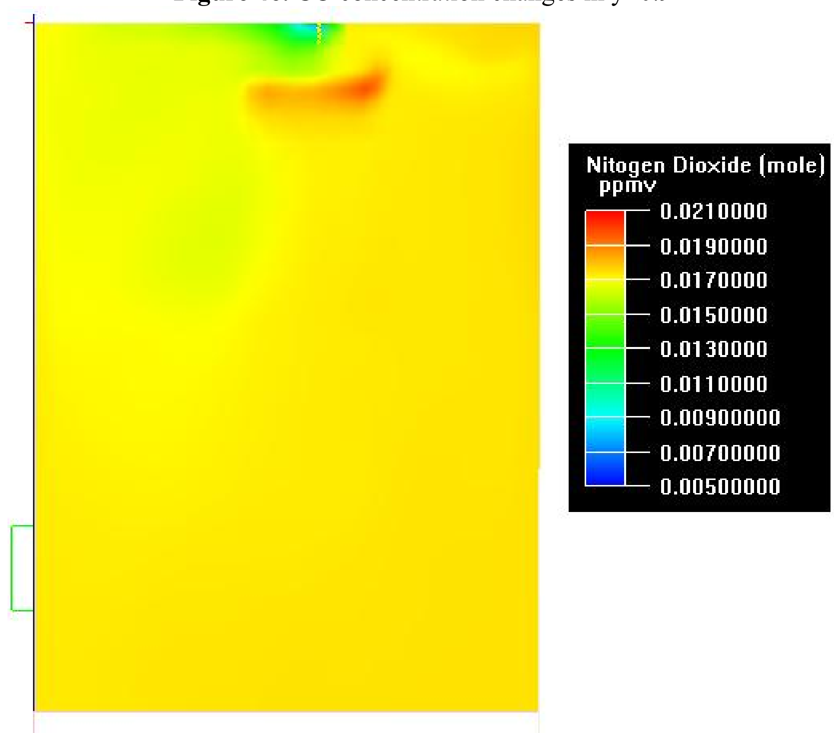

Figure 47. NO_2 concentration changes in y=0.9

CONCLUSION

In this paper, numerical simulation was performed to determine the characteristics of air flow as well as the concentration of pollutants exiting from chimney-free fireplace. A simulation model was set up and verified. Two different rooms were simulated and their results were presented in the frame of profiles of temperature change, radiation temperature change, relative humidity change, speed changes, and pollutants distribution change. The obtained results have revealed that the employed method can well determine the profiles of air flow and predict the way of distributing the pollutants. Furthermore, the use of PMV index clarifies the presence or absence of comfort and prevents any confusion in this regard. CO concentration and the particulate pollutants counted in each room are within acceptable standards for health and a safe environment.

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