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Numerical investigation on a smoke management system in an administration building's atrium

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ABSTRACT

Smoke is considered the major reason of killing a lot of people in case of the building fire because of the reduction of visibility and asphyxiation fatalities occurred in the smoke event. The present research illustrates a numerical simulation on smoke propagation and smoke control for atrium in an administration building and investigates the effect of exhausting smoke by multi point extraction through rooftop exhaust fans on smoke layer height inside the atrium. ANSYS-FLUENT solver is used to solve two-dimensional Reynolds-averaged Navier-Stokes equations (RANS) combined with K-ε Realizable turbulence model for different study cases in an atrium. Two dimensional rectangular plan that is located at the center of atrium is simulated with the dimensions of 25m width and 20m height using T-squared fire with maximum heat release rate of 5 MW for 180 seconds. All parameters are predicted at vertical levels of 2, 13 and 17 m height from the ground floor. Results show that exhausting the smoke through rooftop exhaust fans maintain the smoke layer at higher level from the ground and has better effect on tenability conditions at human level, increasing make up air inlets levels adversely affect smoke layer height which reduce visibility at human level. Finally, the spacing between extract fans outlet is considered a major factor that should be optimized in order to avoid the plug-holing phenomena.

Keywords: *CFD, Atrium, Smoke propagation, Visibility, Heat release*

1. INTRODUCTION

Atrium is considered one of the modern building elements that have been towards which most of architects are adapted in recent decades [1]. An atrium is an element in a building that connects two floors or more by architectural openings -with covered at the top of those openings in two or more successive floors [2]. Atrium has a lot of benefits for architecture designers as is used for purposes like elevator hoist way; escalator opening; or utility shaft which used for plumbing, electrical and air conditioning. Fire causes are different from building to another according to the building type for example cooking fires is in the top list of fires reasons in high rise building used for public assembly secondly smoking is the main reason of fires in commercial places[3]. Most of medical reports demonstrated that fire-related deaths are attributable to smoke inhalation rather than burns. Smoke has been generated by fire in buildings with a high temperature which towards to the ceiling because of buoyancy force followed by the smoke layer which propagated to other attached building spaces and reducing the visibility that affected on occupants through escaping duration. The effect of toxic gases such as carbon monoxide (CO) on human life is highly dangers and it depends on the exposure time. Meanwhile exposure to toxic gases with a high temperature for a period can cause incapacitation and burns. Smoke species which produced from fire could be reduced the visibility for occupants which affected on occupants escaping speed that increase evacuation time from the building that means more exposure to high temperatures and toxic gases so the main factors that effect on operation of fire fighters and the occupants evacuation time are air temperature and exposure time. The main target of the smoke management system is to meet national building codes for occupant safety with keeping the tenability conditions for building occupants during evacuation and the fire-fighters [4].

Chow et al. [5] one of the previous conducted work which had been published in the same field of smoke management system and they discussed the outputs data which generated from experimental tests in a PolyU/USTC atrium which used for the purpose of fire experimental tests. They noticed that the heat release rate is adversely affecting the smoke layer interface height and the smoke layer temperature values. However, the relationship between them is very complicated and also they noticed that the excessive mass flow across the smoke layer interface might be affected on the smoke layer.

Qina T.X. et.al [6] they made the numerical simulation with Fire Dynamic Simulator and validate the results with experimental results for PolyU /USTC atrium and discussed the effect of fire source location which demonstrated that the center of atrium is the most critical case for the smoke layer height.

Zhuyang Han, et.al [7] in this work, the effect of human movement on smoke spread was studied with numerical investigation. The numerical results presented that the human movements are reason for great changes to the velocity and temperature fields in the building.

2. FIRE SOURCE DESCRIPTION

The fire is simulated in two-dimensional as transient fire with heat release rate 3 MW and fast growth rate with 180 seconds ramp up time. Exhaust fans are sized with (10000 m3/hr.) for each to extract amount of smoke sufficient to keep the smoke layer at 1.8 meters from the ground floor to prevent the occupants from smoke layer exposure according to the below equations.

2.1 Rates of Smoke Mass Production for Axisymmetric Plume

The axisymmetric mass flow is according to NFPA-92 [2]

$$Z_l=0.166\times Qc^{2/5} \qquad (1)$$

When $Z > Z_l$

$$m = [0.071 \times Q_c^{1/3} \times Z^{5/3}] + [0.0018\times Q_c] \qquad (2)$$

When $Z \leq Z_l$

$$m=0.032\times Q_c^{3/5}\times Z \qquad (3)$$

The convective portion of heat release rate of the fire shall be determined from Equation.4

$$Q=X\times Q_c \qquad (4)$$

$$T_{st}=T_o+(K_s\, Q_c/m\, C_p) \qquad (5)$$

$$\rho= (P_{atm} / R\, T_{st}) \qquad (6)$$

3. NUMERICAL MODEL DESCRIPTION

3.1 Geometry

Four floors with a total height of 20 m as shown in Figure 1 are presenting our atrium with a rectangular shape. The atrium is including two doors with dimension of (3 * 1) meter for each door in both right and left hand sides in addition to two windows with dimension of (1*1 meter) for each window, the extract fans are distributed on roof with space distance between each other is 3.5 meter as shown in Figure 1.

The fire pool is located at the center of the atrium and area of (2 m2) and because of the previous work demonstrated that the most critical case for smoke layer height event when the fire source is located at the center of atrium [6].

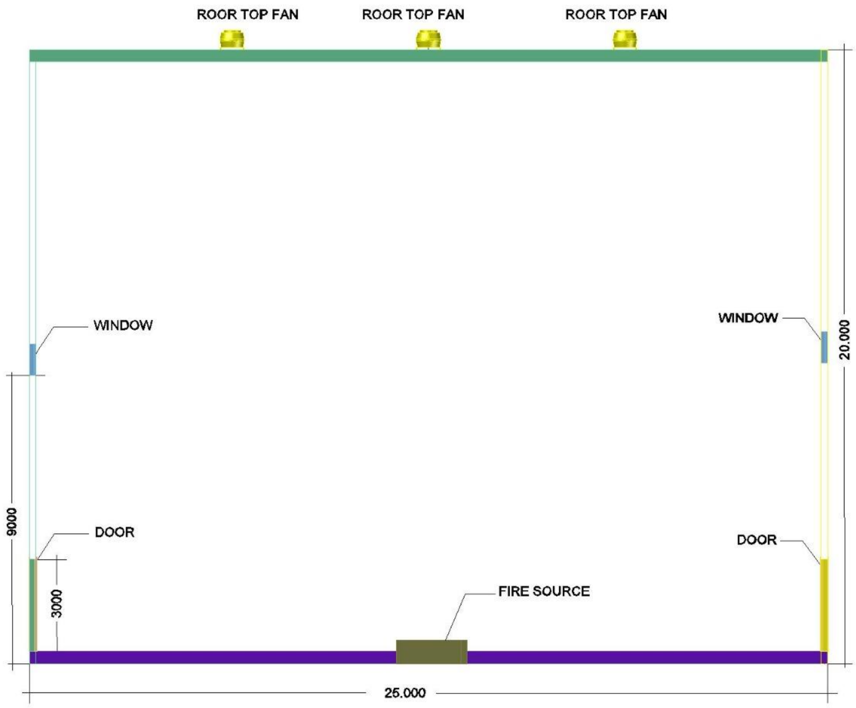


Fig. 1: Schematic diagram of the atrium case study

3.2. Mesh Model

Obtaining high quality grids for the present domain is considered one of the most important procedures for performing a successive simulation. ANSYS ICEM meshing tool was used for generating the mesh for the corresponding atrium domain. Three different levels of grid refinement were produced for performing the grid independency study which is recommended to obtain the optimum balance between solution accuracy and computational cost. Coarse, medium and fine grids were generated using the structured grid topology for the entire domain insuring fine grids near the wall in order to achieve the recommended y+ value of the selected turbulence model. The natural ventilation case (case -1) was used for grid independency study and the results of each grid computation were presented as the obtained clear height after reaching a steady state of a stable developed stage and compared together as shown in table.1 According to the predicted results, the fine grid was chosen and generalized for all present computations.

Table 1: Grid independency test details

Grid	Maximum spacing [m]	Total number of cells	Predicted clear height [m]
Coarse	0.2	20160	0.76
Medium	0.1	80602	0.65
Fine	0.05	161202	0.6

3.3 Numerical Procedures

Various numerical procedures were optimized in order to obtain the results for the current simulations with high accuracy. The corresponding fire scenario was modeled using the ANSYS -FLUENT solver by the mean of multi-species flow approach in order to simulate the fire resultants as a smoke which consist of (Co2-Co-H2o-O2), this approach is widely used and accepted for its numerical simplicity. Transient simulations were carried out using the K-ε Realizable turbulence model for modeling all specified species and flow variables as it shows superior results in case of free shear flows [8]. The coupled solver has been used for pressure-velocity coupling which is recommended for species transport problems including buoyancy effects. The pressure was solved using the body force weighted technique; whereas the second order upwind scheme was obtained for other flow variables [9]. The transient simulations were conducted using a time step size of 0.05 seconds and the iterative solution is considered converged as the residuals for all variables were below the value of (10^{-4}) for each time step.

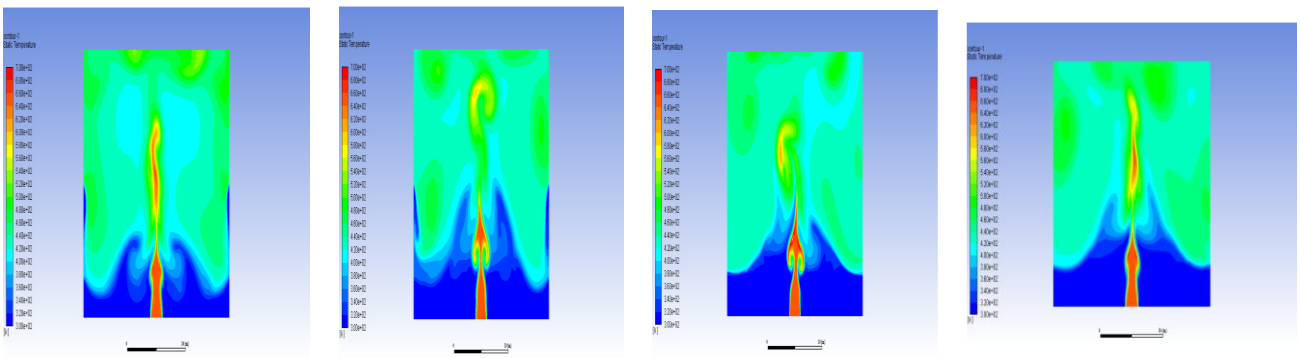
4. CASE STUDY DESIGN AND CONFIGIRIUTIONS

The main boundary design conditions of the atrium smoke management system are illustrated as shown table 2 four different cases were studied as outlined. [10]

Table 2: Design and Geometrical Configurations (Assuming that ambient temperature inside atrium is 25 C)

Name	Exhaust flow rate	Make up air
Case -1	No mechanical smoke exhaust	Make up air through three doors with flow rate 3 m3/s for each door and 1 m3/s for each window
Case -2	Extraction of smoke using Three rooftop exhaust fan (each 2.8 m3/s)distance between them are 3.5 m	Make up air through two doors with flow rate 3 m3/s for each door and 1 m3/s for each window
Case -3	Extraction of smoke using Three rooftop exhaust fan (each 2.8 m3/s)distance between them are 3.5 m	Make up air through two doors with flow rate 3 m3/s for each door and close all windows
Case -4	Extraction of smoke using Three rooftop exhaust fan (each 2.8 m3/s)distance between them are 1.5 m	Make up air through three doors with flow rate 3 m3/s for each door and close all windows

5. RESULTS

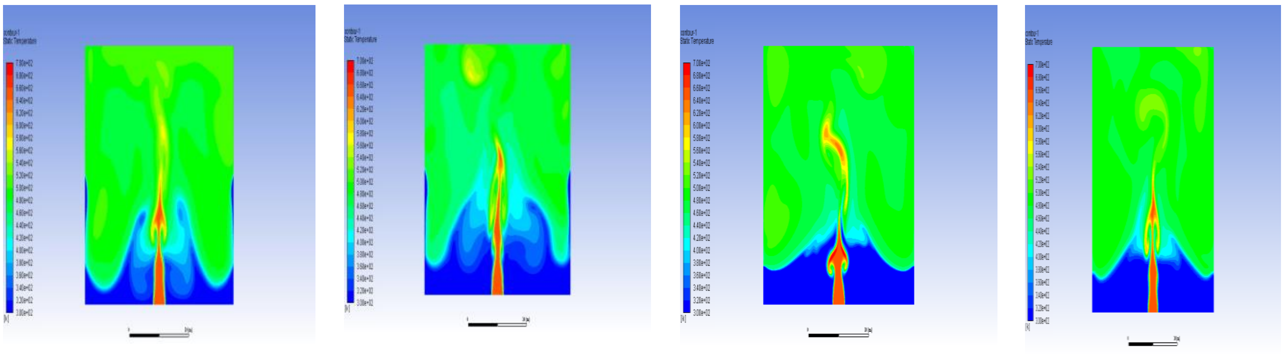


a. Case. 1 b. Case 2 c. Case 3 d. Case 4

Fig. 2: Temperature Contours after 60s

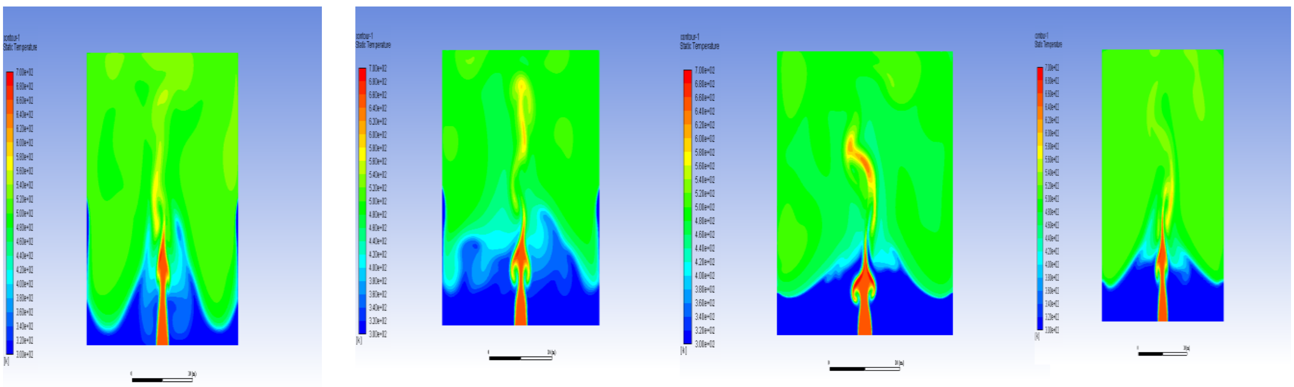
Figures (2-16) show the temperature, velocity, Pressure, carbon dioxide (Co_2) and carbon monoxide (Co) contours in the four cases and after 60, 120 and 180 seconds and it is noticed that the smoke layer propagation is more faster in case of no mechanical fans than in case of there is mechanical extraction system and it was cleared in height of the smoke layer in case-1 reached to 0.6

meter from the ground floor which shall effect on occupants while the height of the smoke layer in case-2 and case-3 reached to 1.8 meter and 3.4 meter respectively which sufficient to avoid the occupants to be smoke layer exposure. However, we noticed that in case-2 the smoke layer height affected by the high level make-up air and the excess of make-up flow rate which make the height of smoke layer reached to 1.8 meter after 180s while the height of smoke layer in case -3 with close the high level make-up air inlets (windows) reached to 3.4 meter from the ground floor and that shall be effected on the visibility, and the exposure time for occupants to smoke layer temperature. Also we noticed that from the same figures in case -4 that the smoke layer height is decreasing to reach to 2.2 meter after 180s in spite of all windows are close but the space distance between the smoke extract fans are reducing to be 1.5 meter which effected on the smoke layer height.



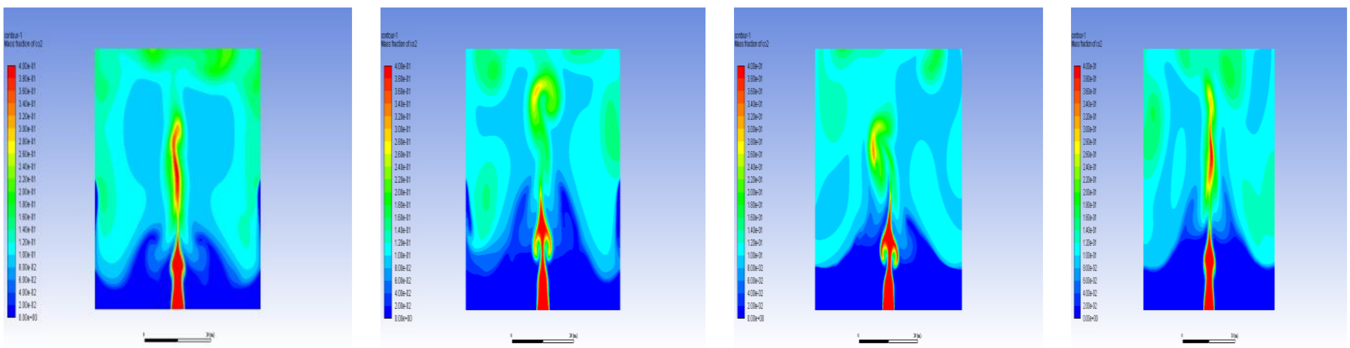
a. Case. 1 b. Case 2 c. Case 3 d. Case 4

Fig. 3: Temperature Contours after 120s



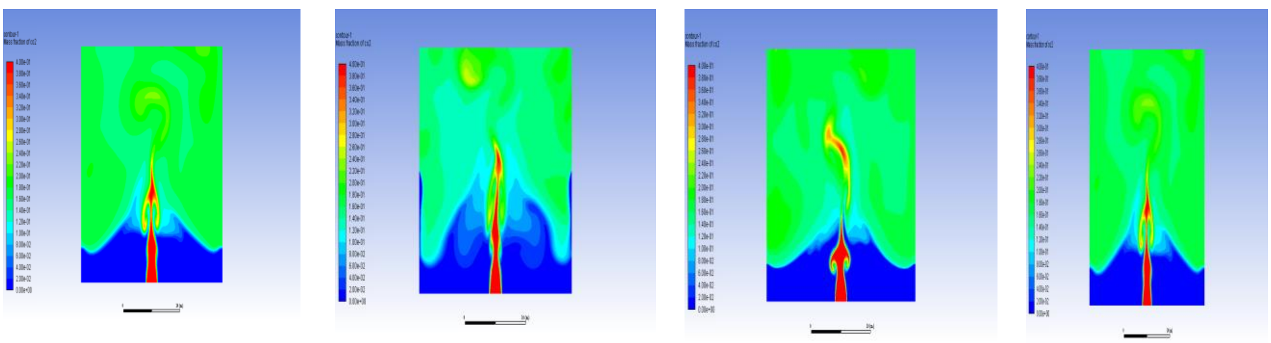
a. Case. 1 b. Case 2 c. Case 3 d. Case 4

Fig. 4: Temperature Contours after 180s



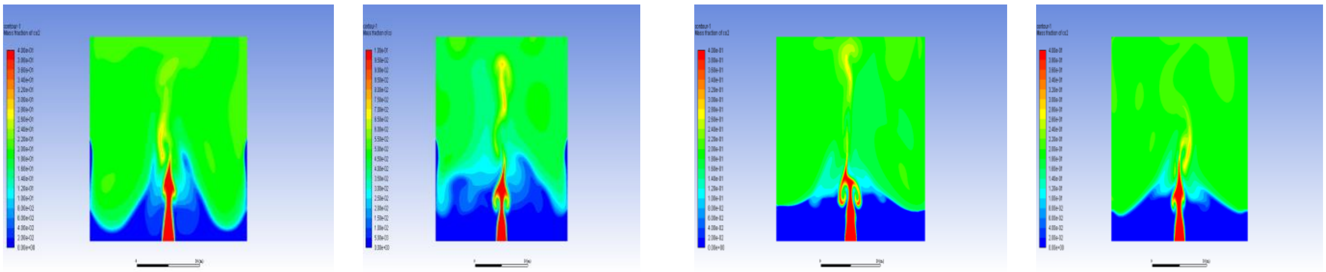
a. Case. 1 b. Case 2 c. Case 3 d. Case 4

Fig. 5: Mass fraction of Co2 Contours after 60s



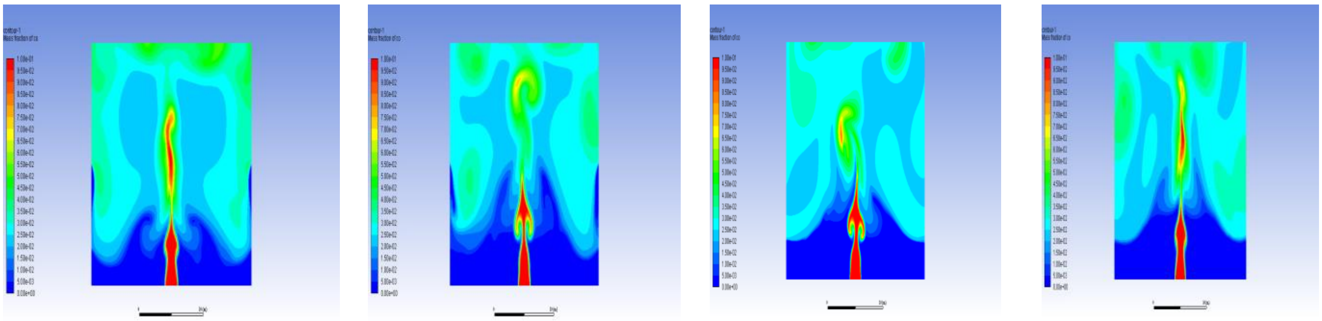
a. case 1 b. case 2 c. case 3 d. case 4

Fig. 6: Mass fraction of Co2 Contours after 120s



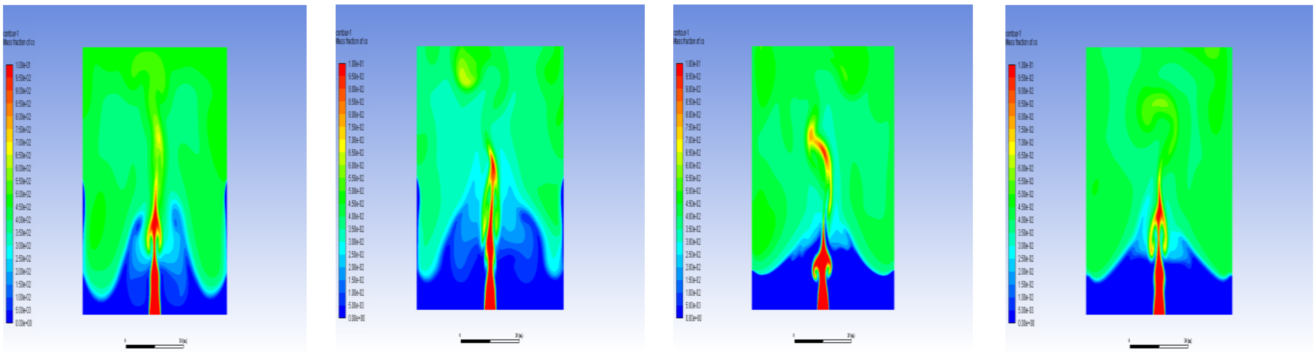
a. case 1 b. case 2 c. case 3 d. case 4

Fig. 7: Mass fraction of Co2 Contours after 180s



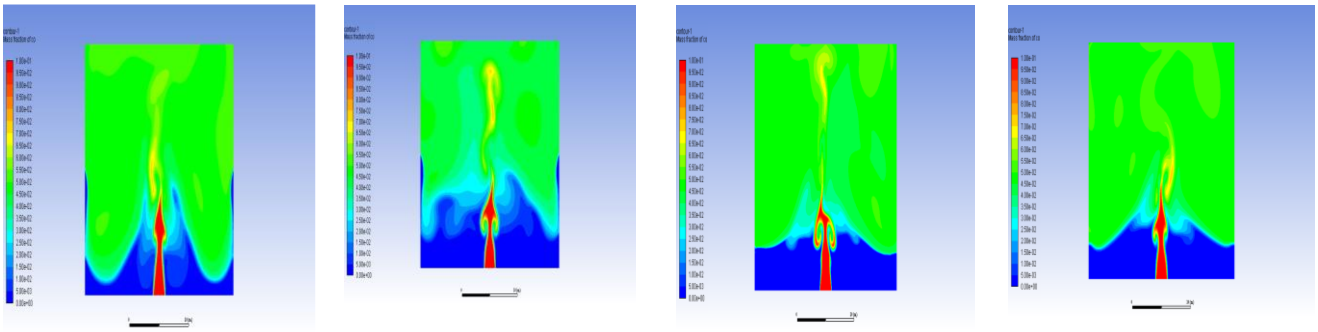
a. case 1 b. case 2 c. case 3 d. case 4

Fig. 8: Mass fraction of Co Contours after 60s



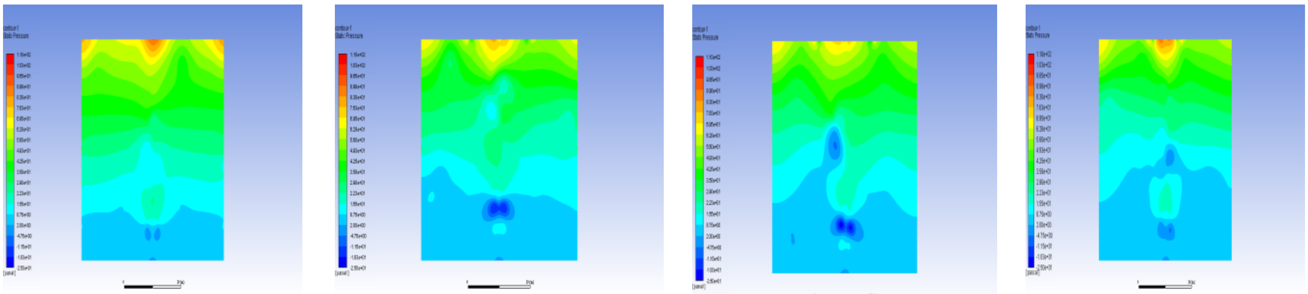
a. case 1 b. case 2 c. case 3 d. case 4

Fig. 9: Mass fraction of Co Contours after 120s



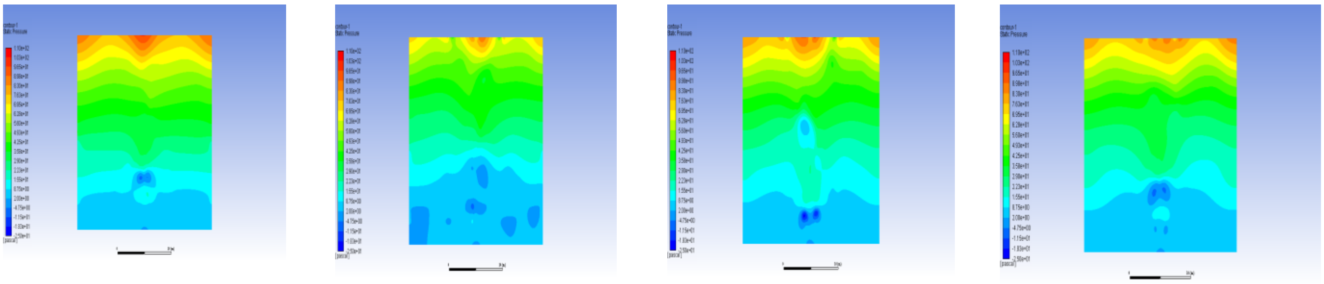
a. case 1 b. case 2 c. case 3 d. case 4

Fig. 10: Mass fraction of Co Contours after 180s



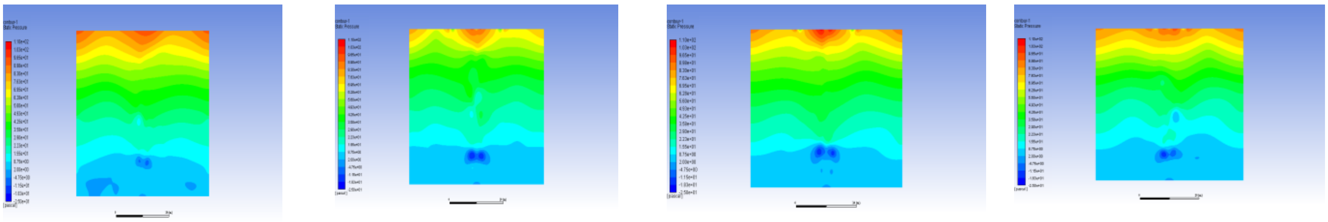
a. case 1 b. case 2 c. case 3 d. case 4

Fig. 11: Pressure Contours after 60s



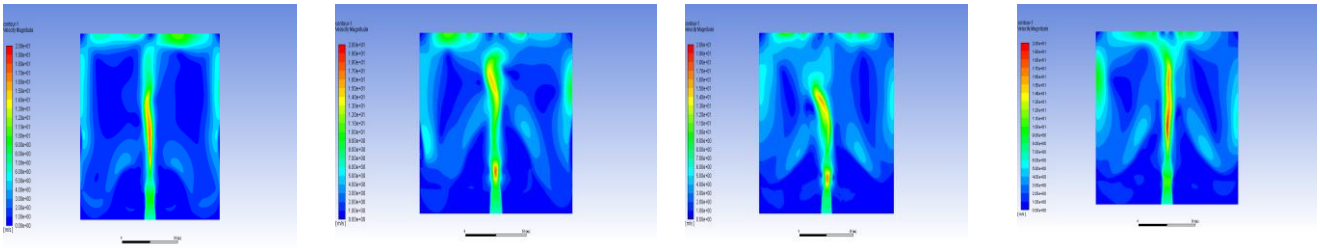
a. case 1 b. case 2 c. case 3 d. case 4

Fig. 12: Pressure Contours after 120s



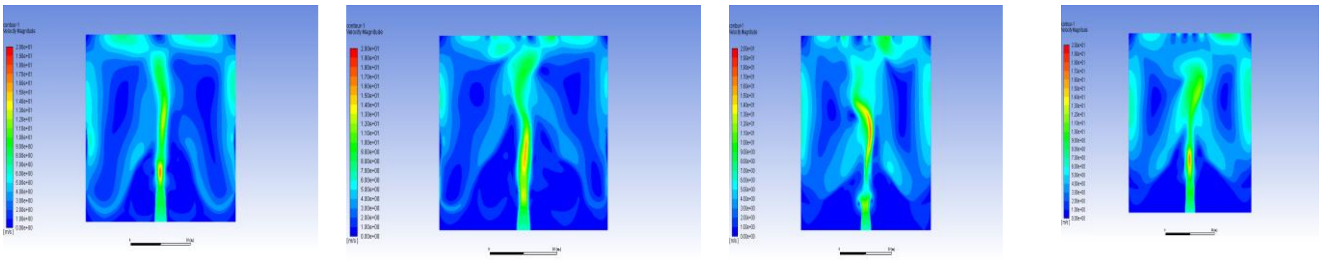
a. case 1 b. case 1 c. case 1 d. case 1

Fig. 13: Pressure Contours after 180s



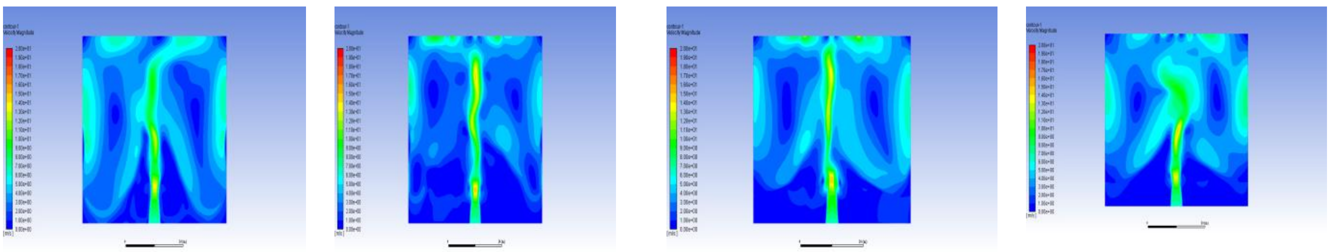
a. case 1 b. case 2 c. case 3 d. case 4

Fig. 14: Velocity Contours after 60s



a. case 1 b. case 2 c. case 3 d. case 4

Fig. 15: Velocity Contours after 120s



a. case 1 b. case 2 c. case 3 d. case 4

Fig. 16: Velocity Contours after 180s

Parameters of temperature, mass fraction of Co2 and mass fraction of Co_2 are plotted in three different locations as shown in figure 17

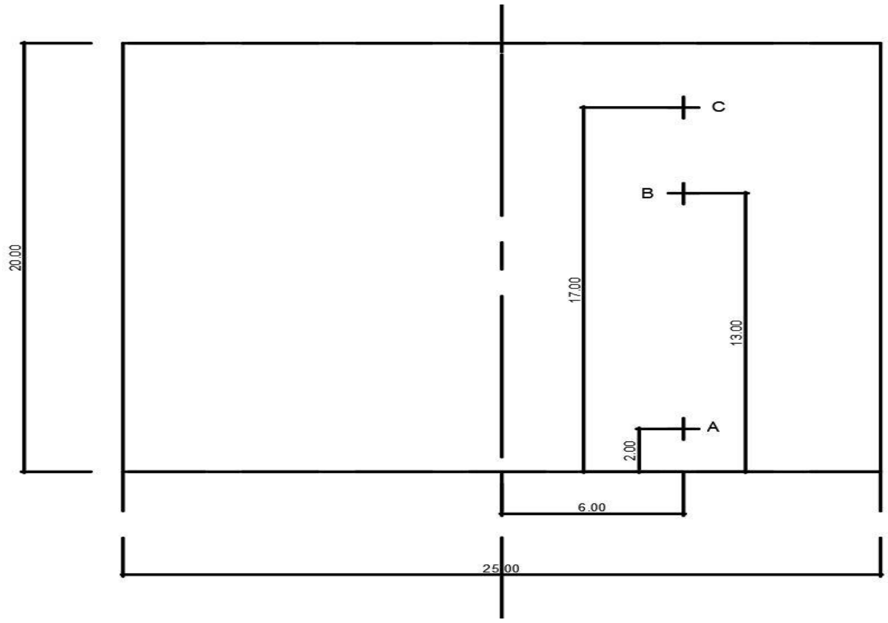


Fig. 17: Schematic diagram indicating the three measuring point's locations (dimensions In Meter)

As shown in figure 18 the smoke layer temperature reached 310 k which is higher than the ambient about 10 k and this value is reached after time 120s and this plotted at level point A while in level point B, C the smoke layer temperature reached 530 k which is higher than the ambient about 230 k as shown in figure 20 and figure 21.

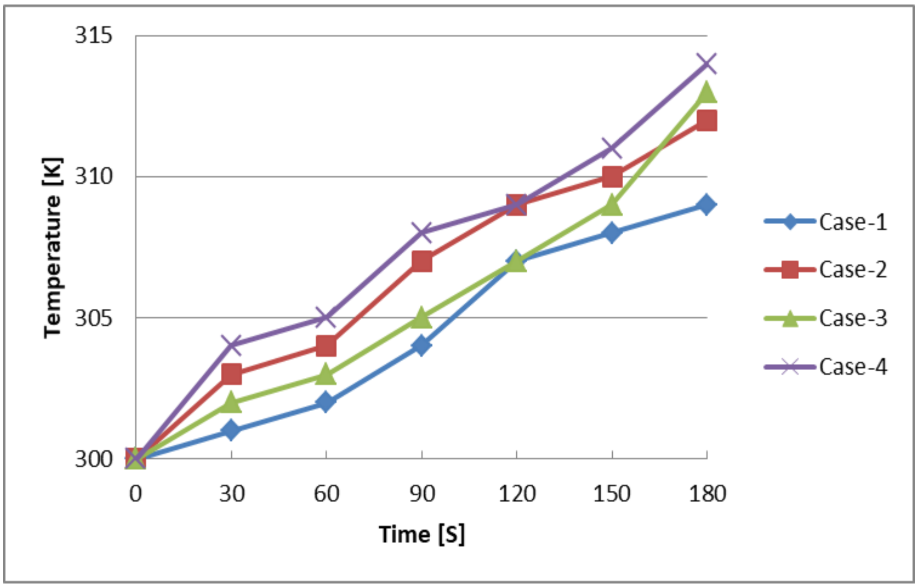


Fig. 18: Predicated temperature distributions at point A with different cases

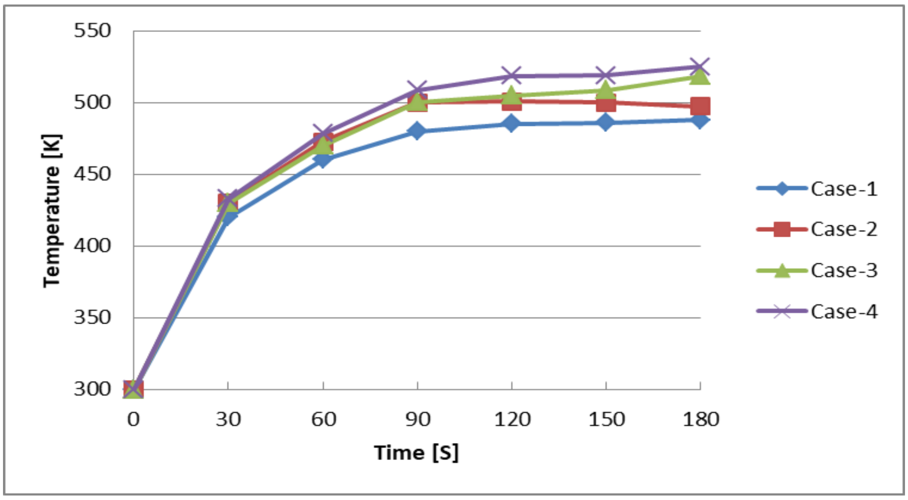


Fig. 19: Predicated temperature distributions at Point B

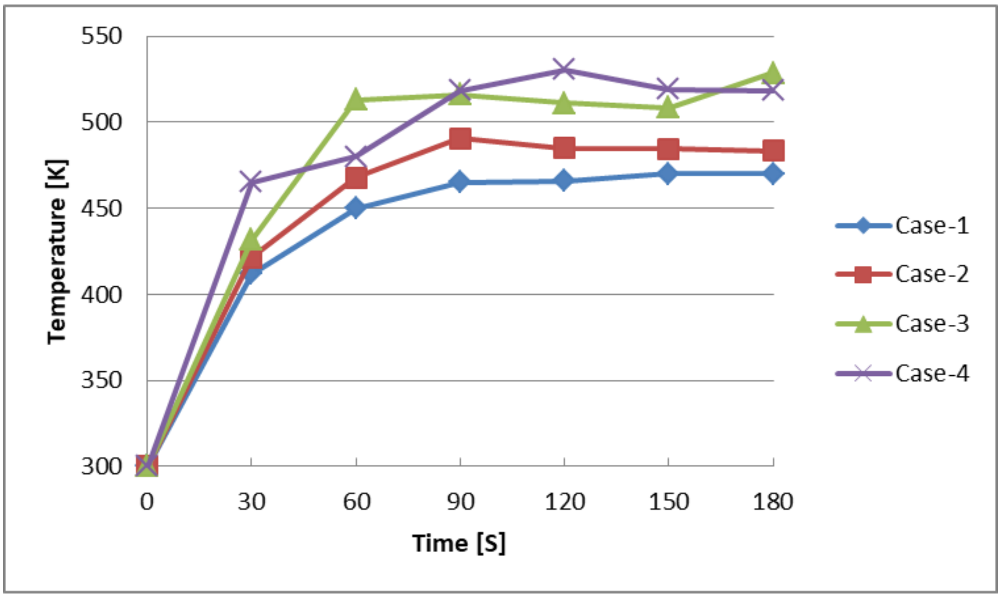


Fig. 20: Predicated temperature distributions at Point C

Figures [21-24] present the mass fraction of Co and Co_2 during the fire event for different cases and at levels B, C which indicates that the concentration of Co and Co_2 are increase in higher levels in case of mechanical ventilation more than without mechanical exhaust fans. As point A is located in clear zone for all simulated cases the mass fractions of Co and Co2 at that location are too small values tend to zero.

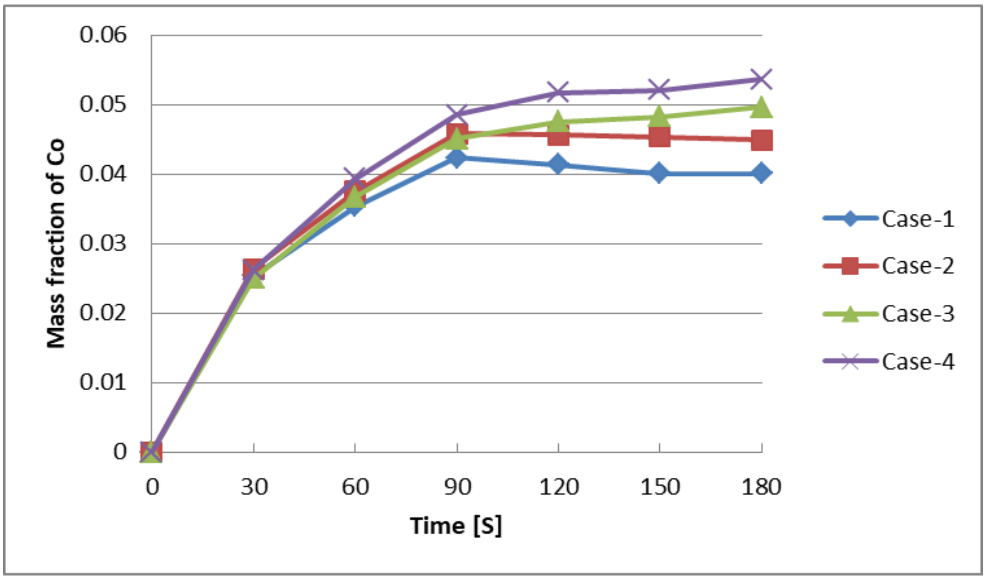


Fig. 21: Predicated mass fraction of Co distributions at point B

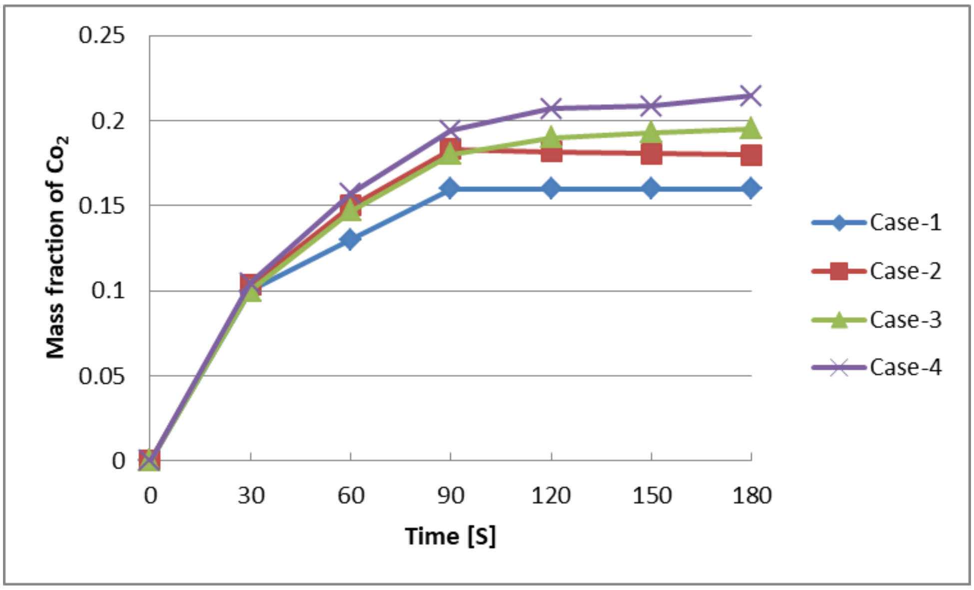


Fig. 22: Predicated mass fraction of Co_2 distributions at Point B

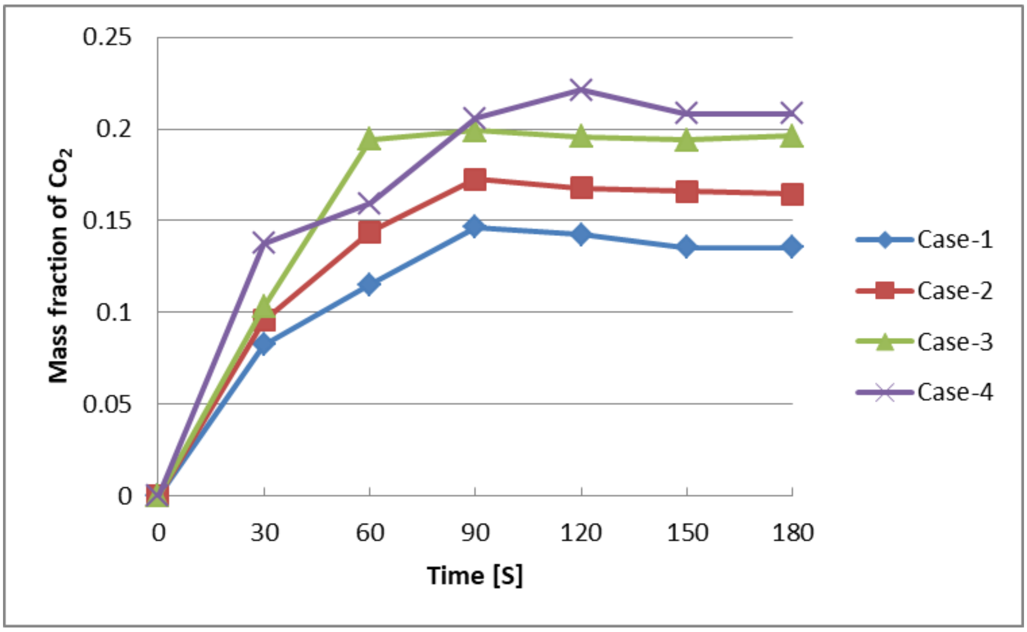


Fig. 23: Predicated mass fraction of Co_2 distributions at point C

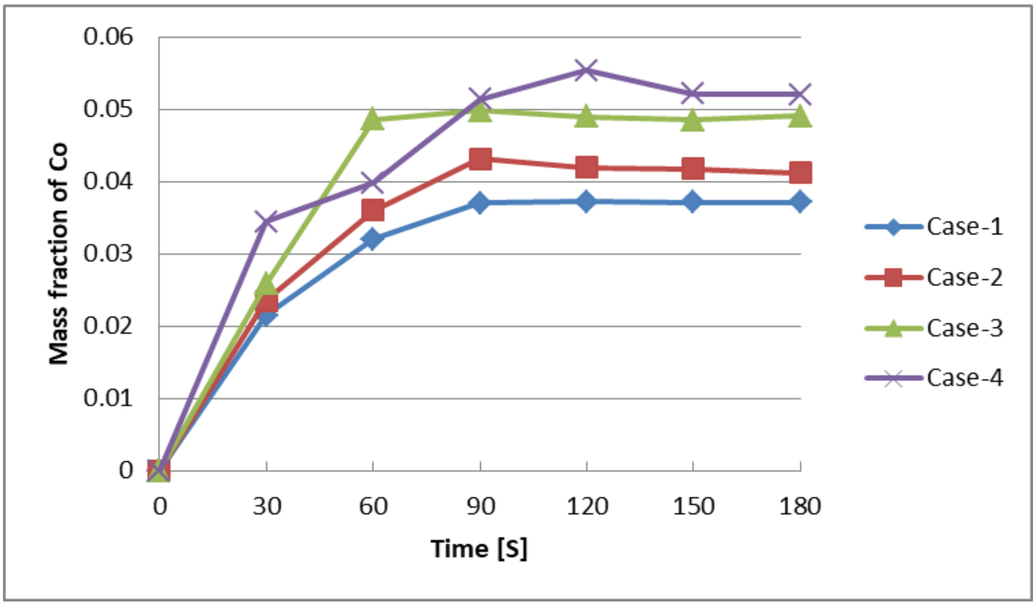


Fig. 24: Predicated mass fraction of Co distributions at point C

6. CONCLUSION

The above results lead to smoke management system is very important in all building with atrium fires, to achieve the tenability conditions it should be used the smoke extract fans in addition to in event of fire it is recommended to control the make-up air flow rate and velocity because of the increasing of make-up air has adversely affecting on the smoke layer height and the exposure time for human to smoke layer. Finally in case of multiple extract points, the minimum separation distance between exhaust fans should be not less than the root of each fan extraction flow rate to prevent the plug-holing phenomena.

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APPENDIX

Z_l = limiting elevation, m.
Q_c = convective portion of heat release rate, KW.
Z = distance above the base of the fire to the smoke layer interface, m.
Q_c = convective portion of heat release rate, KW.
X = convective fraction (dimensionless).
Q = heat release rate of the fire, KW.
m = mass flow rate in plume at height Z, kg/sec.
ρ = density of smoke at temperature (kg/m3)
P_{atm} = atmospheric pressure (Pa)
R = gas constant (287)
T_{st} = smoke layer temperature (°C)
T_o = ambient temperature (°C)
K_s = fraction of convective heat release contained in smoke layer.
Q_c = convective portion of heat release (kW)
m = mass flow rate of the plume at elevation (kg/sec)
C_p = specific heat of plume gases (1.0 kJ/kg-C)
The value of (1.0) shall be used for the fraction of convective heat release contained in the smoke layer, Ks, unless another value is substantiated in accordance with test data.

