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CARBON POLLUTION CONCENTRATIONS PROGNOSTICATION: CASE STUDY OF ROAD POLLUTION IN CONCEALED TUNNELS

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ABSTRACT
Air pollution carries significant risks for human health and the environment. Vehicles powered by fossil fuels are major contributors to air pollution. In order to reduce carbon related ailments among road users, the polluted air in our roads need to be decarbonized. The aim of this paper is to present a two dimensional grid based numerical carbon pollution model prognosticating carbon pollutant concentrations in roads, generated by car exhausts with a case study of concealed tunnels. The results of the findings on concentration of carbon pollutants in concealed road tunnels with ventilations and ventilation fans on road sections of the tunnel have been presented. Forced convection has been brought in by introducing suction pumps and accelerating the air into the tunnel to achieve the desired results. Godunov finite volume technique is used to help in prognosticating carbon pollutant concentrations at different levels from the source. With the technique, it has been possible to predict the carbonaceous deposits in the atmosphere and the effect of forced convection on concentration of carbon pollutants from the source.

KEYWORDS: Keywords: *Advection, Diffusion, Convection, Prognosticate, Modeling.*

1. INTRODUCTION
Air quality has been a factor that influences the acceptance of road construction and road passage in most major towns world over. Therefore, research in this area is of crucial significance. Hence, this study is about airflow and carbon pollution at street-level and the effect of road design on reducing the concentration of carbon pollutants and limiting human exposure to such pollutants. Ambient air concentrations of pollutants are frequently highest along highways (Baumgarter et al, 2014; Rangland, 2012). Research in this area shows that embankments on roads do not generate emissions but rather they confine and redistribute emissions produced by vehicles passing through the road section. Zhang and Gao (2009) found that these levees act as topographic impediments which cause drag and produce turbulence to compensate for the deformation of the flow field when wind flows above them. This is because they influence carbon pollutant concentrations around them by blocking initial dispersion. They also increase turbulence and initial mixing of the emitted pollutants (Gromek et al, 2008). From his research discussions, Spim et al (1986), predicted that unless vented, closed spaces like tunnels or parking garages do not allow for proper dispersion of air pollutants. This coupled with the problem of traffic jam which is a common problem in most roads leading into and out of major cities in the world can lead to serious health challenges. Exhaust gases which consist of carbon, a component of particulate matter is a cause of health problems in human beings (Kodjak, 2015). Rossman (2015) too in his research work showed that carbon has adverse effects on human health. According to official statistical data obtained by Teimuraz (2012), air pollution is more pronounced in urban areas with heavy traffic than that in industrial areas. Kenyan cities have not been spared from this menace and it is expected that the continuous economic growth today being experienced will increase the traffic intensity therefore, worsening the quality of air. This coupled with daily increase in intensity of traffic as a result of increase in number of both private and public vehicle users, necessitates a greater control of emissions from combustion engines (Oke et al, 2011). Thus, investigation of dispersion of exhaust gases on Kenyan highways by means of mathematical modeling is inevitable in giving insight on human health, environmental management and future economic planning.

Further to this, there is mounting evidence that local concentrations of air pollutants are greatly affected by the physical form of the city in terms of the street size and height of buildings on the sides of the streets. However,

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there have been relatively minimal attempts to improve street level air quality through manipulation of road design. Such designs if integrated with other measures can play a vital role in enhancing dispersion of carbon pollutants and in limiting human exposure in areas where pollutants are highly concentrated (Michael, 1947). Such an approach is hampered by the fact that few urban designers have clear scientific understanding of the factors that affect the generation and dispersion of air pollutants (Spim et al, 1986). Research has it that air pollution is a public health problem in most cities in the developing world as in these parts of the world, 'second hand' cars are greatly in use. Epidemiological studies show that air pollution in developing countries accounts for tens of thousands of excessive deaths and billions of dollars has been used in medical costs over the years (Asif et al, 1996). Tong et al, (2012) and Wang, (2011) studied the impact of road side barriers on pollutants concentration and revealed that there is a potential for the vertical uplift of airflow over the barrier and the possibility of plume attachment further downwind of the recirculation zone. This situation results in higher pollutant concentrations behind the barrier at further distances than for equivalent distances with no barrier present (Baldauf et al, 2008; Gayle et al, 2010). Therefore, modern road constructions currently witnessed in major cities in Kenya may be of health concern if not checked. Most existing models developed by researchers have shown that exposure to carbon (II) oxide (CO) which is a component of carbon as a result of staying on the road for long hours leads to reduced lung function, courted chest pain, increased chances of asthma, unleashed free radicals to the catalyze carcinogens in the blood and activated cellular process that might at some point lead to heart attack. However, most researches have shown lack of mechanistic understanding of how roadside barriers and forced convection influence pollutant transport and concentration in and near roadways especially under different meteorological conditions and barrier properties such as underpasses and ventilated embankments on highways and highways fitted with gadgets that provide forced convection. Goyal and Anikender (2008) though did not incorporate ventilated embankment and forced convection which affects the physical parameters such as concentration, advection and diffusion, did an extensive research on air pollution in roads in Indian urban and documented the effect of pollution as a health hazard. Due to lack of such information from researchers, a good number of road embankments and underpasses are today still being constructed without ventilation that would assist in the free flow of air-pollutant mixture. The diagram below is an illustration of concealed embanked road with dilution mechanism.

In Figure 1, forced convection has been incorporated by fitting suction pumps on the embankments in addition to the ventilation fans to provide free stream to propagate advection.

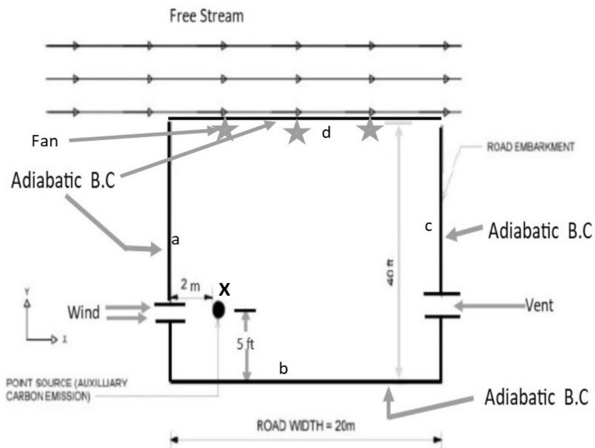

Figure 1: Concealed Embankments.

2. MATERIALS AND METHODS

2.1 The Governing Equation

The governing equation used to describe the Mathematical model used in this research paper is a combination of known 2-D advection - diffusion equation presented inform of partial differential equation together with the equations of conservation laws - the continuity, momentum and energy equations. These equations are shown in equation (1) below.

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$$\begin{cases} \frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} - D(\nabla \cdot \nabla)C + R - S = 0 \\ \frac{\partial \rho \vec{V}}{\partial t} + [(\rho \vec{V} \cdot \nabla)\vec{V}] + \nabla P - \rho g + S_V = 0 \\ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) - S_\rho - S_D = 0 \\ \frac{\partial E}{\partial t} + \nabla \cdot (E\vec{V}) + \nabla \cdot (P\vec{V}) - S_E = 0 \end{cases} \quad (1)$$

The PDE equation in the first equation of equation (1) derived from the mass conservation principle describes carbon pollution by vehicles on roads in the absence of forced convection (when R is not factored in) and in the presence of forced convection, incorporating ventilated embankment as a parameter where: (x, y) is position of the receptor relative to the source, $c = c(x, y, t)$ is carbon pollutant concentration at $c(x, y)$ and time t in (kg/m^3), u is wind velocity component (m/s) in the x-direction, D_x *, and* D_y are Coefficients of turbulent diffusion in x-direction and y-direction respectively in (m^2/s) which reduces degree of freedom between pollutants, S is source term in (sec^{-1}) which controls emission of pollutants and helps in describing the hydrodynamic equation fully and R is dilution term or decaying of pollutant rate due to sink in (sec^{-1}) which represents changes caused by chemical reaction.

The numerical solutions in the next section have been obtained by considering a two dimensional advection-diffusion equation (1) with a rectangular domain of interest measuring $20m \times 40ft$ illustrated in Figure 1. Carbon particles are assumed to be continuously released at a constant rate from source point which is taken to be at a height of $5ft$ and at horizontal distance of $2m$ from the embankment.

It is taken that all measurements must be made at the center of the control volume as shown in Figure 2. The discretization will be for the p^{th} control volume.

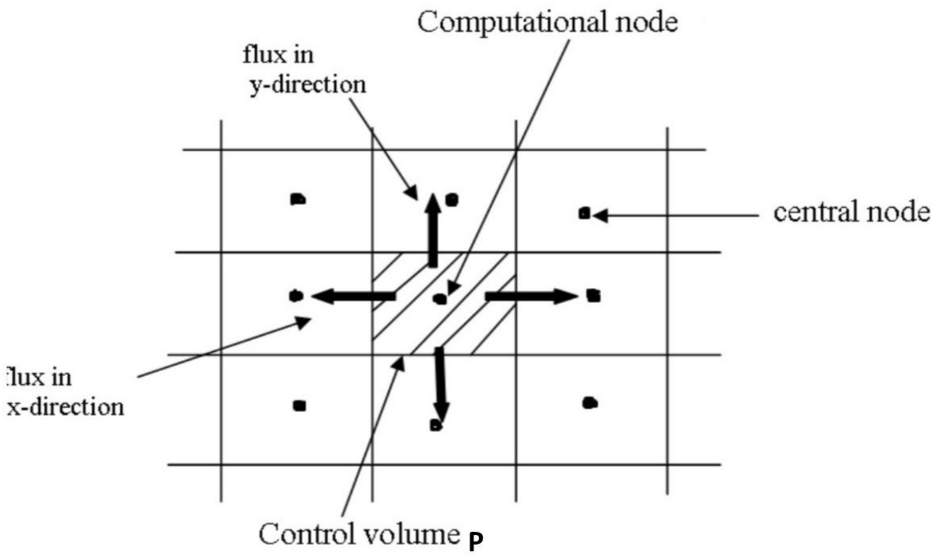

Figure 2: Control Volume and Fluxes.

Boundary Conditions

Since differential equations inevitably have lots of solutions, a way in which we can deduce uniqueness is by imposing suitable initial conditions and boundary conditions. Boundary conditions for the Navier-Stokes equations are in many ways similar to the solutions of the convection-diffusion equation. Since our problem is a boundary value problem, we need to have a set of additional constraints called boundary conditions alongside the differential equations to enable us solve our differential equation in a specified domain. The initial conditions we need here are function-valued initial conditions that are assumed under the cold start assumptions. That is, $c(x, y, o) = 0$ for all $x > 0$ and $y > 0$. The boundary conditions required for the carbon flow calculation and are associated with our problem are derived from the Dirichlet boundary conditions for total absorption and the Adiabatic boundary conditions as is illustrated in the diagram below.

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Dirichlet Boundary Conditions

Dirichlet boundary conditions are value specified which means that the value of a variable is given at the boundary. This is to help us specify the value of the function on the surface. For example, zero carbon concentration shall be set at the walls. Also at the upstream boundary the carbon concentration shall be given as

$$\begin{cases} \rho = 0, at\ x = 0 \\ \rho = 0, at\ x = h \end{cases} \qquad (2)$$

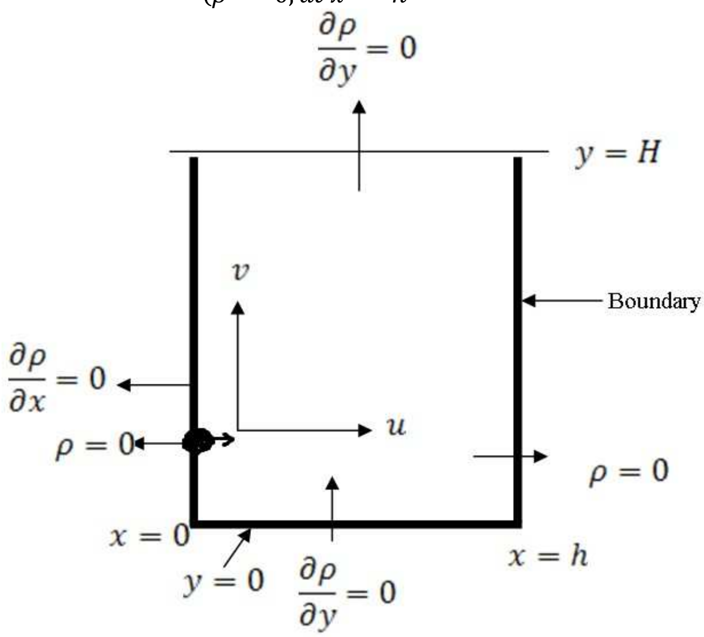

Figure 3: Boundary conditions

Adiabatic Boundary Conditions

Adiabatic boundary conditions refer to conditions under which overall heat transfer across the boundary between the thermodynamic system and the surroundings is absent. In our case we assume that the embankments are boundary walls that are adiabatic. Hence,

$$\begin{cases} \frac{\partial \rho}{\partial x} = 0, at\ x = 0 \\ \frac{\partial \rho}{\partial x} = 0, at\ x = h \\ \frac{\partial \rho}{\partial y} = v_y \rho, at\ y = 0 \\ \frac{\partial \rho}{\partial y} = 0, at\ y = H \end{cases} \qquad (3)$$

for all $t > 0$, where h is the length of the domain in x-direction, H is the height of the inversion layer and v_y is the dry decomposition velocity of the primary pollutant (m/s).

Numerical Scheme

In this section the advection - diffusion transport equation and conservation laws of mass, momentum and energy have been coupled and then discretized into weak form using Godunov Finite Volume Method (GFVM). In this discretization technique the PDEs are reduced into first order systems of equations with the highest order terms taken as source terms. The method is based on integration of the governing equations over control volume (*CV*) to reduce them into coupled system of algebraic equations shown in equation (2.3) below. The amount of carbon pollutants in each cell and the fluxes across the cell are computed in mesh geometry to provide data used for analyzing the flow by performing simulations using a matlab software.

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$$\begin{cases} \rho = \frac{-R(U)+S(U)}{\delta t[k+u]\delta x \delta y} \\ \frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = S_\rho + S_D = 0 \\ \frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(P + \rho uv) + \frac{\partial}{\partial y}(\rho uv) = 0 \\ \frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(\rho uv) + \frac{\partial}{\partial y}(P + \rho vv) = -\rho g + S_V \\ \frac{\partial E}{\partial t} + \frac{\partial}{\partial x}u(E+P) + \frac{\partial}{\partial y}v(E+P) = S_E \end{cases} \quad (4)$$

Thus, we express our discretized conservation laws in the form:

$$U_t + F(U)_x + G(U)_y = S(U)$$

and take $P = a^2\rho$ hence; the last four equations of equation (4) becomes:

$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ E \end{bmatrix}, F = \begin{bmatrix} \rho u \\ \rho(uu + a^2) \\ \rho uv \\ u(E + a^2\rho) \end{bmatrix}, G = \begin{bmatrix} \rho v \\ \rho uv \\ \rho(vv + a^2) \\ v(E + a^2\rho) \end{bmatrix}$$

where, E is the total Energy per unit mass. ρu is momentum, $\rho(u^2 + a^2)$ is momentum flux in the x-direction, $\rho(v^2 + a^2)$ is momentum flux in the y-direction, ρu^2 and ρv^2 are advective fluxes in the x and y directions respectively. The products $\rho(x,t)u(x,t)$ *and* $\rho(y,t)v(y,t)$ give the densities of momentum in the x and y directions respectively. U is a column vector of conserved variables $\rho, \rho u, \rho v$ and E. $S = S(U)$ is a source term. Body forces such as gravity are represented in S. Injection of mass, momentum and energy are also included in S. Flux vectors $F = F(U)$ and $G = G(U)$ are functions of the conserved variable vector U, and Fx, Gy are fluxes due to convection and viscous.

3. RESULTS AND DISCUSSION

In the preceding section a computational numerical model to estimate the concentration of the carbon pollutants emitted from a point source at the point $(2m, 5ft)$ first into a region with and secondly without advective removal mechanism and transformation process in xy-plane rectangular domain presenting vertical cross-section of the road tunnel is presented. Extraction mechanism presented in the domain is wind streaming at a height of 2 meters through an aperture drilled on the embankments on both the left and right side of the road. The experiment analyzes the diffusion of carbon particles from the point source and removal of carbon particles from the domain by both free and forced convection, and we have presented simulation of carbon pollution control situation using two scenarios labeled, simulation 1, and simulation 2.

Simulation 1: Carbon Pollution Dispersion in a Domain of Ventilated Embankment in the Absence of Forced Convection

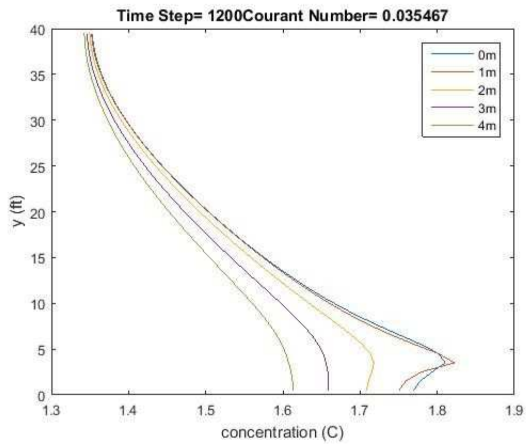

Figure 4: Concentration level sets of carbon pollutant after approximately 20 minutes

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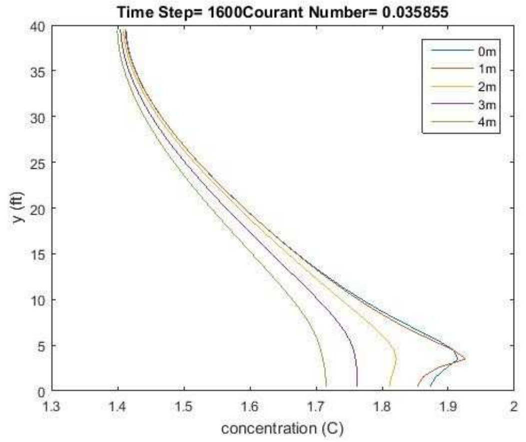

Figure 5: Concentration level sets of carbon pollutant after approximately 27 minutes

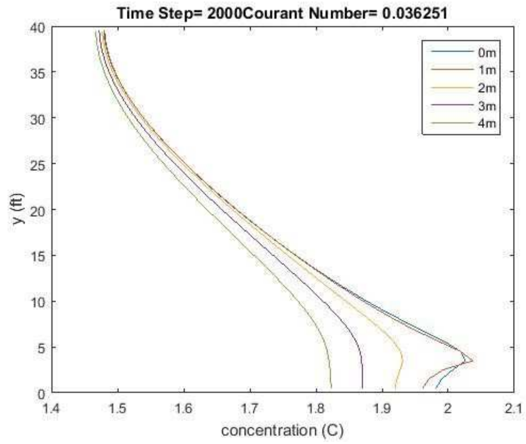

Figure 6: Concentration level sets of carbon pollutant after approximately 34 minutes

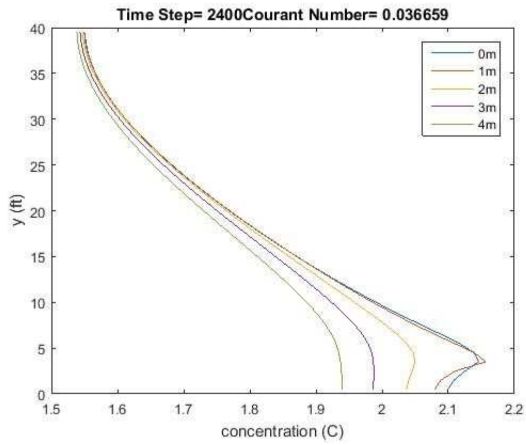

Figure 7: Concentration level sets of carbon pollutant after approximately 41 minutes

The results of air density variation for each control volume are represented by level sets $(\rho - \rho_o)$, giving the difference between densities of pure air (ρ_o) and air contaminated with carbon particles (ρ) where $\rho > \rho_o$. These concentration levels at different times are plotted in Figure 4 to Figure 7, indicating the spread of carbon particles from the source is affected by the embankment. The concentration profiles at different distances and heights for different time lines plotted in the figures which show that the concentration of carbon particles is higher in the

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region close to the source point but spread out slowly. This is an indication that advection and convection are limited by presence of embankments which confine the carbon emissions from the source. The results also show that concentration of carbon pollutant is higher at ground level compared to the region above the source, which could be attributed to molecular weight of carbon particles compared to that of air affecting diffusion process. The concentration of pollutant is further seen to increase with time at different distances for given heights which may be as a result of continuous production of pollutants from the exhaust but at faster rate compared to the rate of production and this may be due to diffusion processes.

Simulation 2: Carbon Pollution Dispersion in a Domain of Ventilated Embankment in the Presence of Forced Convection

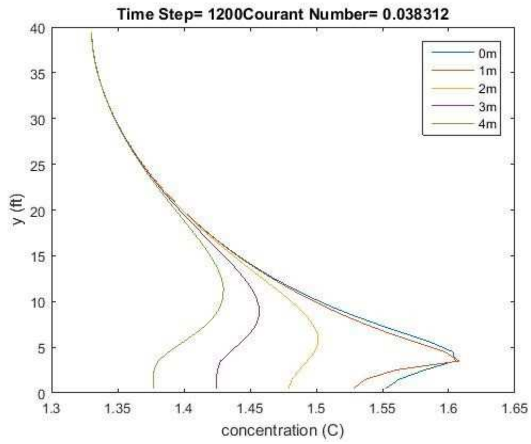

Figure 8: Concentration level sets of carbon pollutant after approximately 20 minutes

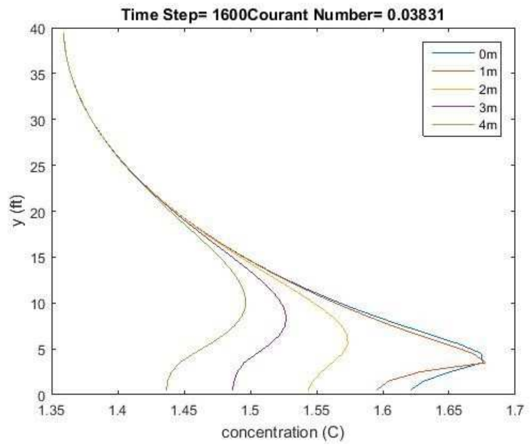

Figure 9: Concentration level sets of carbon pollutant after approximately 27 minutes

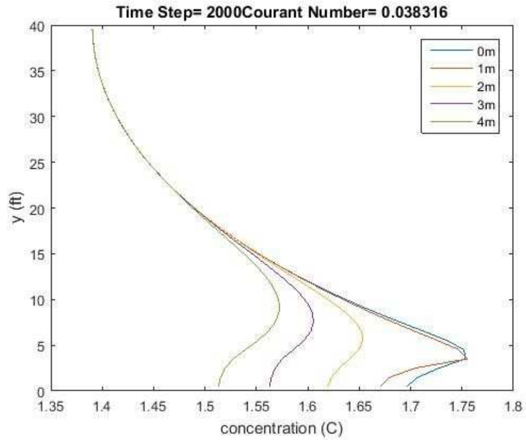

Figure 10: Concentration level sets of carbon pollutant after approximately 34 minutes

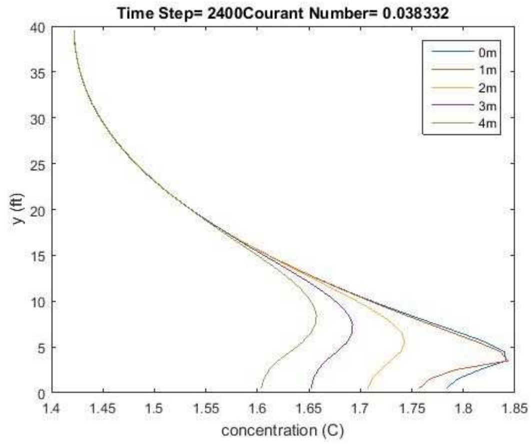

Figure 11: Concentration level sets of carbon pollutant after approximately 41 minutes

To demonstrate the effect of forced convection on the concentration of pollutant within roads with embankments, we have changed environmental parameter by increasing the wind speed from zero to 30*m/s* into the domain through a ventilation at (0,4) node by means of suction pump. The solutions show that advection and convection are improved by the presence of forced convection. Concentration profiles at different heights and distances for different time steps are plotted as is illustrated in Figure 8 to Figure 11. It can be observed that the concentration of carbon particles is increased upwards and decreased downwards from the source. This can be attributed to increased convection process leading to the reduction of carbon particles in the enclosure. For higher concentration, the concentration levels are closely packed which is the case with simulation 1, while for lower concentration the concentration levels are spread out which is the case with simulation 2 and this may be due to the dominating wind effect on extraction of carbon particles. Comparing the results of simulation 1 and 2, it is seen that the rate of dilution within the region increases with time in the presence of faster extraction rate than in the absence of advection. At coordinates $(15m, 35ft)$, in the absence of forced convection, the concentration of pollution above that of pure air is $0.29g/cm^3$ while in the presence of forced convection, the concentration of pollution above that of pure air is $0.14g/cm^3$ after approximately 41 minutes. This demonstrates that forced convection has doubled the extraction rate of pollutants from the domain.

4. CONCLUSION

Time dependent two dimensional mathematical model for predicting carbon pollution in a road tunnel subjected to variation in environmental factors is presented in this paper to simulate the dispersion process of the carbon pollutants along roadway with ventilated embankments. The numerical model computes the deviation of air density $(\rho - \rho_0)$ due to carbon emitted from a point source. In both cases it is clear that embankments confine pollutants. The dispersion mechanism plays an important role in reducing the concentration of the carbon

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pollutants everywhere in the region within the domain. The results indicate that there is minimal effect of free convection on the dispersion rate as the concentration of pollutants is higher at the ground level. In the case of forced convection, deviation in density of air due to pollutants is observed to be minimal.

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