LARGE EDDY SIMULATION TO ASSESS THE EFFECTIVENESS OF NATURAL CONVECTION VENTILATED SMOKE DUCTS TO PROTECT EMERGENCY STAIRCASE

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Abstract: *Computational Fluid Dynamic (CFD) is used in this work to simulate a fire and the smoke movement in a high building. The main goal of this work is to assess the effectiveness of natural ventilated smoke ducts to protect emergency staircases. Two design concepts are compared. The first system is constituted of a single duct for inflow of fresh air and outflow of smoke. The second concept has a double duct in order to separate the fresh air inflow from the outflow of smoke. The investigation of this effectiveness is of great importance for Fire Brigades and Fire-Safety Engineers in Brazil. Large Eddy Simulation (LES) is used to calculate the turbulent flow of the smoke in the building. The combustion process is described by the mixture fraction approach. The process of the thermal radiation uses the equation of radiation transport for a gray no-scattering gas. There are simulated two buildings of 18 m and of 36 m of height. The fire scenario is a fire focus in the 1st. floor of the buildings with the smoke moving, through the smoke duct into the upstairs floors. The effectiveness of the natural ventilation ducts to protect the emergency staircase is evaluated by the evaluation of the temporary evolution of the temperature in the 4th. and 10th. floors. In both cases the extraction of the smoke is caused by the natural convection. It is verified that, in the second case, the smoke contaminates very quickly the upstairs floors. In this case, the smoke cannot exhaust to the atmosphere, because the duct is closed at the top floor. From the obtained results, analyzing the evolutions of temperatures in the 4th. and 10th. floors, it can be concluded that the first case of a duct has a better effectiveness in avoiding the smoke contamination in the staircase and compartments of the building.*

Keywords: *Combustion, Computational Fluid Dynamic, Large Eddy Simulation, Fire-safety Engineering*

1. Introduction

Fire-smoke movement in buildings has been investigated by Mitler (1991) and more recently by Drysdale (1997) and K. B. McGrattan (1994). The understanding or prediction of smoke movement is very important to fire-safety engineering. In Brazil, this issue was investigated by Vittorino (1998) using the integral or zone model. There is a controversy regarding the protection of emergency staircases, as can be seen in the Brazilian Federal Norm (ABNT, 1993) and the Municipal Legislation of São Paulo City (LM/SP, 1992). The main goal of this work is to contribute, using CFD modeling, to investigate the efficiency of natural ventilation ducts to protect emergency staircases.

The computational research in fire dynamics has shown preferential tendency to shift the zone model towards to field models techniques. The rapid growth of computing power and the corresponding maturing of computational fluid dynamics (CFD), has led to the development of field models applied to fire research problems. In the present work, the approach of Large Eddy Simulation is used. The feature of this model is the description of turbulent mixing of the gaseous fuel and combustion products with the local atmosphere surrounding the fire. This mixing process, which determines the burning rate in the fire and controls the spread of smoke and hot gases, is extremely difficult to predict accurately. The basic idea behind the LES technique is that the eddies, that account for most of the mixing, are large enough to be calculated with reasonable accuracy from the equations of fluid dynamics. The small-scale eddy motion can either be accounted for by modeling or ignored (Krieger, 2002). In the used model, the small-scale motion is accounted for by means of the well known Smagorinsky model (Smagorinsky, 1963).

2. The Studied Cases

A sketch of the simulated building is shown in Fig. (1). The objective is to simulate the smoke movement from the fire focus, at the room, toward the exhaust duct at the hall. The main question to be answered is how efficient the natural ventilated ducts are to avoid the contamination of the upstairs floors. The simulated region is the room nearby the hall, the hall itself, which protect a emergency staircase and the exhaust duct. The staircase itself is not simulated. Two buildings are simulated, one of 18 m and other of 36 m high. For each building, two cases are simulated:

- **case 1**- Building with one duct, which serves simultaneously to natural inflow of atmospheric air and exhaust of the gases.
- **case 2**- Building with two adjacent ducts, where one serves only as natural inflow of atmospheric air and another enables the exhaust of the hot gases.

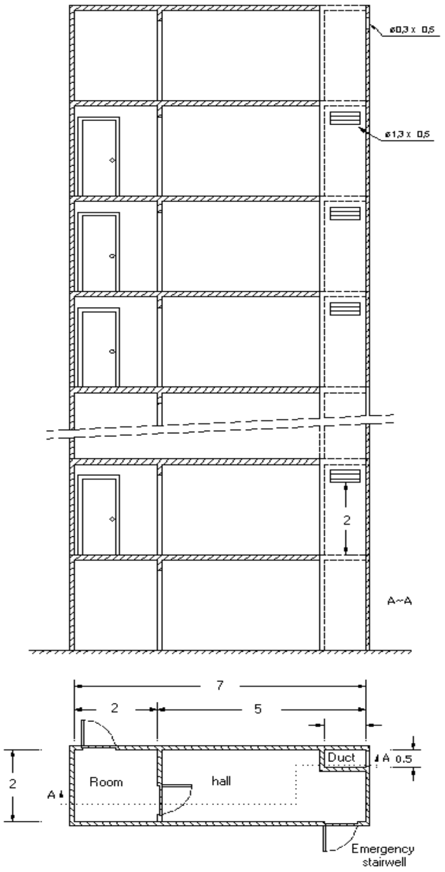

Figure 1. Basic representation of computational domain of studied buildings.

The 18 m high building (ground, plus four and covering floors) has fire-safety doors (FSD) open at the $1st$. and $4th$. floors. The 36 m high building has FSD open at the $1st$., $4th$. and $10th$. floors. All others FSD are closed. The open FSD at the $1st$., $4th$. and $10th$. floors are located between the room and hall. The others FSD are closed, included that serves the emergency staircase. Therefore, the fire-smoke flow evolves from fire plume at the room from the $1st$. floor to the hall. From the hall, the smoke moves upwards either through the exhaust duct or through the fresh air inflow duct, which reveals a shortcoming of the system. This study comprises the verification of smoke contamination inside the room at the $4th$. and $10th$. floors. In fact, the verification is done by following Lagrangian particles emitted on the fire focus at the room. If after a time interval, high temperature, due to particles emitted on the fire focus, is detected in the upstairs rooms, one can also conclude that both smoke and poisoning gases shall be also found there.

3. Mathematical Model

The equations describing the transport of mass, momentum, and energy by the fire induced flows must be simplified so that they can be efficiently solved for the fire scenarios of interest. The mixing and transport of smoke and hot gases is calculated directly from an approximated form of the Navier-Stokes equations. The simplified equations, presented by H.R. Baum and Rehm (1994) for low Mach number, are:

- Conservation of Mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0, \tag{1}$$

where ρ is the density, t is the time and $\vec{V}$ is the velocity vector.
The second term of equation Eq. (1), $\nabla \cdot (\rho \vec{V})$, is the divergence of the flow.

- Conservation of Species:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot \rho Y_i \vec{V} = \nabla \cdot (\rho D)_i \nabla Y_i + \dot{W}_i''' \tag{2}$$

where Y_i is the mass fraction of ith species, D is the diffusion coefficient and $\dot{W}_i'''$ is the production rate of ith species per unit volume.

- Conservation of Momentum:

$$\frac{\partial \vec{V}}{\partial t} + \nabla H = \vec{V} \times \vec{\omega} + \frac{1}{\rho}\left[(\rho - \rho_\infty)\,\vec{g} + \nabla \cdot \tau_{ij}\right], \tag{3}$$

where $\vec{\omega}$ is the vorticity vector, ρ_∞ is the atmospheric air density, $\vec{g}$ is the acceleration of gravity and τ_{ij} is the viscous stress tensor.
The total pressure divided by the density, ∇H, is related by:

$$\nabla H \approx \frac{1}{2}\nabla|\vec{V}|^2 + \frac{1}{\rho}\nabla\tilde{p}, \tag{4}$$

where $\nabla\tilde{p}$ is the pressure perturbation.
The buoyancy $(\rho - \rho_\infty)\,\vec{g}$ is the dominant source of vorticity, while the pressure perturbation influence, $\nabla\tilde{p}$, is small.

- Conservation of Energy:

$$\frac{\partial(\rho h)}{\partial t} + \vec{V} \cdot \nabla(\rho h) - \frac{D(p)}{Dt} + p_0\left(\nabla \cdot \vec{V}\right) = \dot{q}''' - \nabla \cdot \vec{q_r} + \nabla \cdot k\nabla T + \nabla \cdot \sum_i h_i (\rho D)_i \nabla Y_i, \tag{5}$$

where h is the enthalpy of gas mixture, p is the computational domain pressure, p_0 is the background pressure, $\dot{q}'''$ is the heat release rate per unit volume, $\vec{q_r}$ is the radiative heat flux vector, k is the thermal conductivity, T is the temperature and h_i is the enthalpy of ith species.

- Equation of State:

The conservation equations are supplemented by an equation of state relating the thermodynamic quantities. An approximation to the ideal gas law is made by decomposing the pressure into a background component(p_0), a hydrostatic component ($\rho_\infty g z$), and a flow-induced perturbation ($\tilde{p}$), as:

$$p = p_0 - \rho_\infty g z + \tilde{p}, \tag{6}$$

and, with operator ∇ applicated to pressure p, result:

$$\nabla p = \rho_\infty \vec{g} + \nabla\tilde{p}. \tag{7}$$

From ideal gas law:

$$p_0 = \rho T\left(\frac{\Re}{M}\right) = \left(\frac{\gamma - 1}{\gamma}\right)\rho h, \tag{8}$$

where:

$$M = \sum_i \frac{M_i}{Y_i}, \tag{9}$$

and

$$h = T \sum_i c_{p,i} Y_i, \tag{10}$$

hence $\Re$ is the universal gas constant, M is the molecular weight of the gas mixture, M_i is the molecular weight of ith gas species, Y_i is the mass fraction of ith gas species, γ is the ratio of specific heats $\left(\frac{c_p}{c_v}\right)$, where c_p is the constant pressure specific heat and c_v is the constant volume specific heat.

The equations Eq. (1), Eq. (2), Eq. (3), Eq. (5) and Eq. (8) are instantaneous and are applied in LES technique. The divergence of the flow is obtained by taking the product (ρh) of the equation of state (Eq. (8)), and then substituting terms from the energy conservation equation Eq. (5). The energy equation is never explicitly solved, but its source terms are included in the expression for the flow divergence calculation with mass conservation equation Eq. (1). Some approximations was made when assumed, in equation of state, that the density and temperature or density and enthalpy are inversely proportional; as assumed a temperature-independent specific heat of mixture Eq. (10) which was made only to reduce the cost of the calculation. The approximate form of the divergence used in the calculation is:

$$\nabla \cdot \vec{V} = \frac{\gamma - 1}{\gamma p_0} \left(\dot{q}''' - \nabla \cdot \vec{q_r} + \nabla \cdot k \nabla T + \nabla \cdot \sum_i c_{p,i} T \left(\rho D\right)_i \nabla Y_i - \frac{1}{\gamma - 1} \frac{dp_0}{dt} \right). \tag{11}$$

In general, it is not assumed that the specific heat is independent of temperature. The pressure rise term on the right hand side of the divergence expression Eq. (11) is non-zero only if it assumed that the enclosure is tightly sealed, in which case the background pressure p_0 can no longer be assumed constant due to the increase (or decrease) in mass and thermal energy within the enclosure. The evolution equation for the pressure is found by integrating equation Eq. (11) over the entire domain Ω:

$$\frac{dp_0}{dt} = \frac{\gamma - 1}{\vartheta} \left[\int_\Omega \left(\dot{q}''' - \nabla \cdot \vec{q_r} + \nabla \cdot k \nabla T + \nabla \cdot \sum_i c_{p,i} T \left(\rho D\right)_i \nabla Y_i \right) d\vartheta \right] - \frac{\gamma p_0}{\vartheta} \int_\Omega \vec{V} \cdot d\vec{S}, \tag{12}$$

where ϑ is the volume of the simulated domain.

In Large Eddy Simulation, the large-scale eddies are computed directly and the sub-grid scale dissipative processes are modeled. This work make use of Smagorinsky (1963) model, which is commonly used in LES simulations. In an LES calculation, where the grid is not fine enough to resolve the diffusion of fuel and oxygen, a mixture fraction-based combustion model is used. The mixture fraction combustion model is based on the assumption that large-scale convective and radiative transport phenomena can be simulated directly, but physical processes occurring at small length and time scales must be represented in an approximate manner. The model adopted is based on the assumption that the combustion is mixing-controlled. The local heat release rate is computed from the local oxygen consumption rate at the flame surface, assuming that the heat release rate is directly proportional to the oxygen consumption rate. For combustion modeling, the model of Bilger (1980) is used. This combustion model is however not able to predict correctly smoke or particulate formation in flames. Therefore, in this work the smoke is inferred from the temperature fields. Following Lagrangian particles emitted on the fire focus and colored by its instantaneous temperature, one can qualitatively estimate the smoke concentration inside the building. Radiative heat transfer is included in the model via the solution of the radiation transport equation for a non-scattering gray gas. The equation is solved using a technique similar to finite volume methods for convective transport, namely Finite Volume Method (FVM) Huh (1999).

4. Numerical Method

The Fire Dynamics Simulator (FDS) (K.B. McGrattan, 2002) is the code used in the present work. All computations are performed within a computational domain made up of rectangular blocks, each with its own rectilinear grid. The FDS is a computational code which solves three-dimensional unsteady transport equations, that is conservation of mass, species and energy including also a combustion model and thermal radiation equations. The source terms from the energy conservation equation are incorporated into the divergence and ultimately are involved in the mass conservation equation. Each of the conservation equations emphasize the importance of the velocity divergence and vorticity fields, as well as the close relationship between the thermally expandable fluid equations (ideal gas law) and the Boussinesq equations. The temperature is found from the density and background pressure via the equation of state. All spatial derivatives are approximated by second order central differences and the flow variables are updated in time using an explicit second order predictor-corrector scheme.

The computational grid used is defined by $30x20x120$ rectangular box, with 72000 cells in the computational domain. Spatial derivatives in the governing equations are written as second order accurate finite differences on a rectilinear grid. All calculations start with ambient initial conditions. The real time of fire simulated was 120 seconds, for both cases of each building. The code FDS requires a relatively fast CPU and a substantial amount of random-access memory (RAM). This work was simulated using a personal computer Pentium IV with 512 megabytes of memory. The CPU time required for one simulation case was approximately 15 hours.

5. Results

The main goal of this work is to assess the effectiveness of natural convection ventilated ducts to protect emergency staircase. As said before, the adopted combustion model is not able to correctly predict smoke formation in flames. Therefore, the smoke concentration is inferred from the temperature fields. In the following figures, the Lagrangian particles emitted on the fire focus and colored by the instantaneous temperature in two instants - 24 s and 72 s - are presented. The effectiveness of the natural ventilation ducts to protect the emergency staircase is established by the observation of the temporary evolution of the temperature in the ambient $4th$. and $10th$. floors.

The Fig. (2) and Fig. (3) present the temperature evolution the for case 1 - single duct: air inflow and exhaust smoke construction, particles on 24 s and 72 s, 18 m high building. The room on the $4th$. floor receives very low smoke contamination, after 24s until 72s, while the room and hall on the $1st$. floor are completely injured. This evolution of gases movement shows that most of the bulk smoke goes directly towards the outlet grid at the top of the single duct.

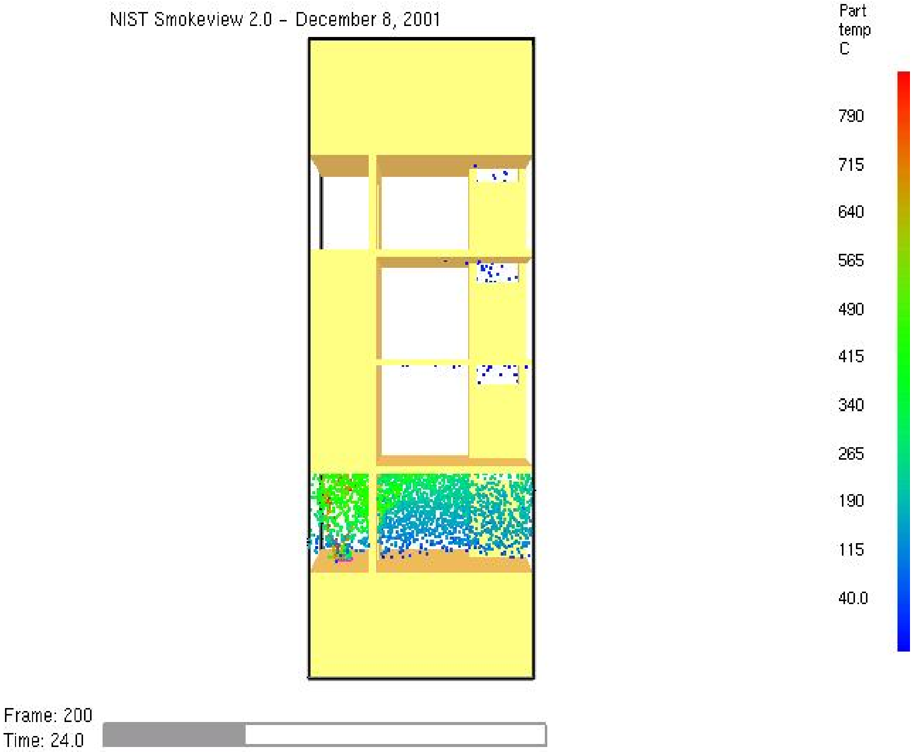

Figure 2. Case 1 - single duct: air inflow and exhaust smoke construction, particles on 24 s, 18 m building.

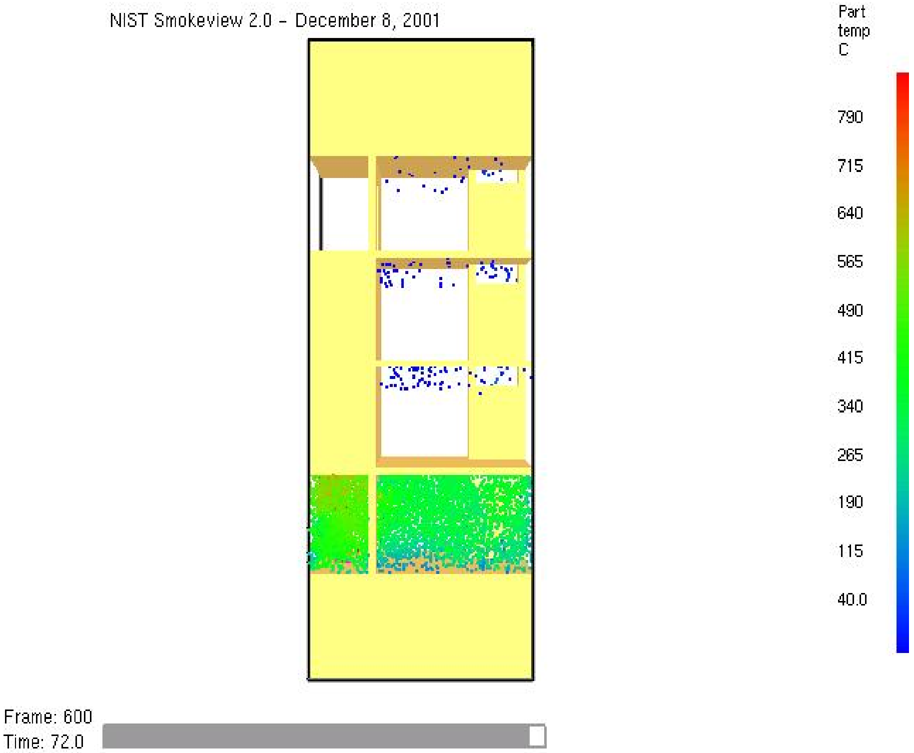

Figure 3. Case 1 - single duct: air inflow and exhaust smoke construction, partícles on 72 s, 18 m building.

The Fig. (4) and Fig. (5) are the visualization of particles contamination for case 2 - double duct: air inflow/ exhaust smoke construction, 18 m high building. These pictures show the room on the $4th.$ floor with grave smoke contamination during the time elapsed of $24s$ to $72s$. This shortcoming of the design concept could be attributed to the closed end, on the covering floor, of the inflow air duct. Once the hot gases has entered into the fresh air duct, it moves upwards, due the buoyancy, and are finally either trapped at the top or goes out of the duct in the hall of the upstairs floors.

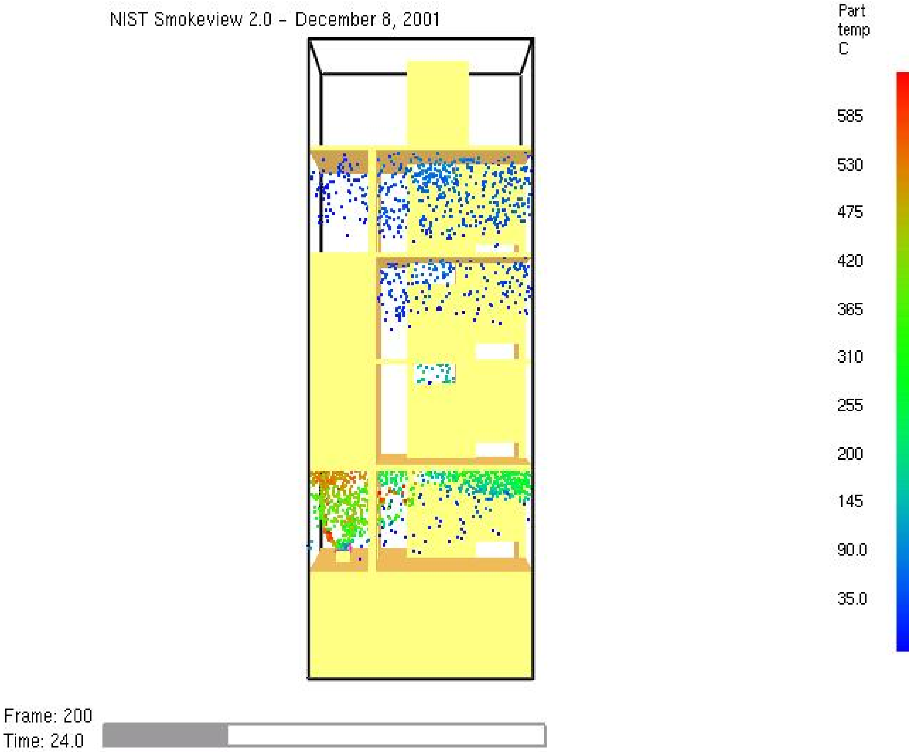

Figure 4. Case 2 - double duct: air inflow/exhaust smoke construction, particles on 24 s, 18 m building.

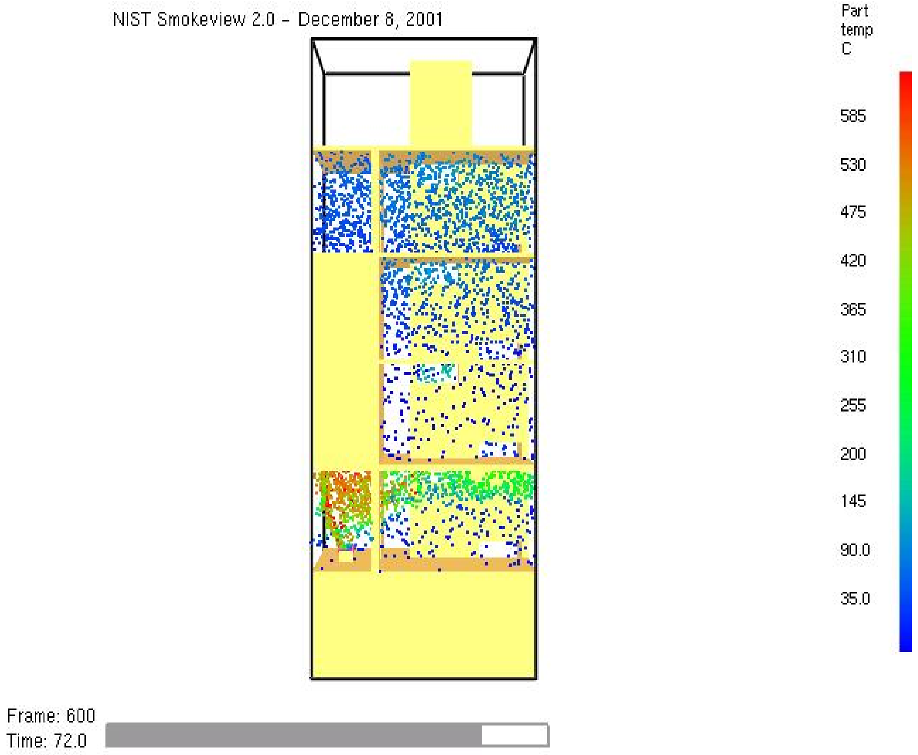

Figure 5. Case 2 - double duct: air inflow/exhaust smoke construction, partícles on 72 s, 18 m building.

The Fig. (6) and Fig. (7) are case 1, 36 m high building. The Lagrangian particles colored by temperature are shown for 24s and 72s. The rooms at the 4th. and 10th. floors exhibit very low smoke contaminations, what indicates that most smoke movement occurs inward the single duct.

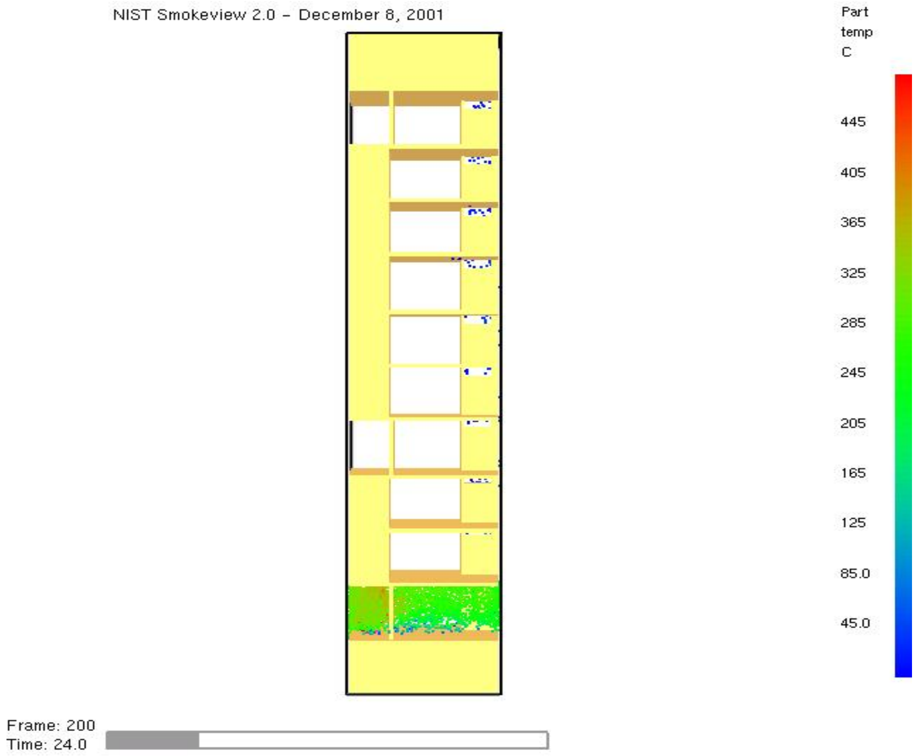

Figure 6. Case 1 - single duct: air inflow and exhaust smoke construction, partícles on 24 s, 36 m building.

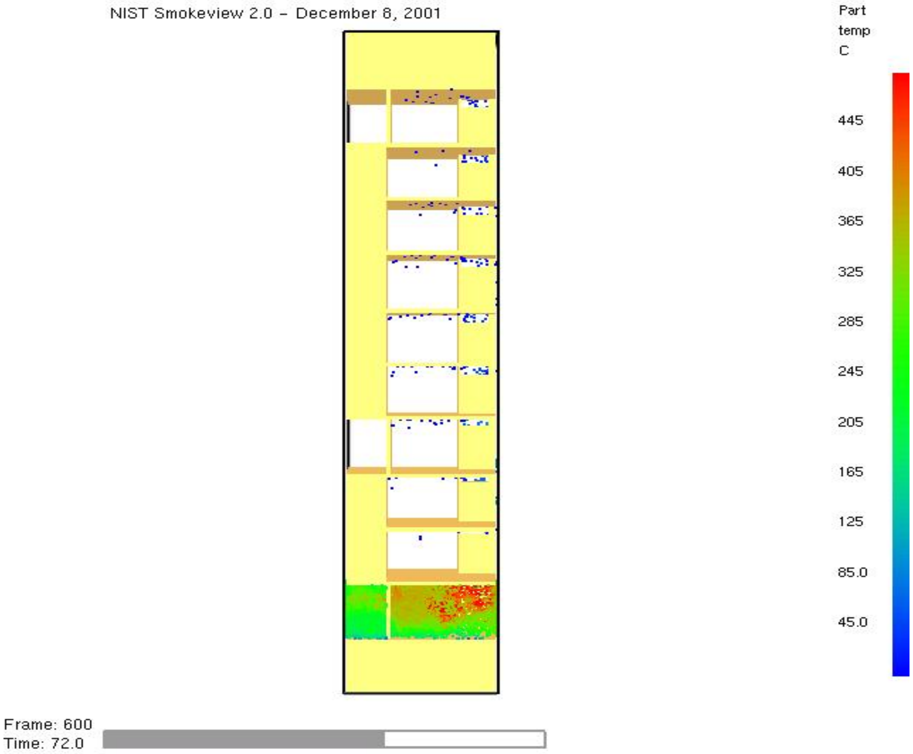

Figure 7. Case 1 - single duct: air inflow and exhaust smoke construction, partícles on 72 s, 36 m building.

The Fig. (8) and Fig. (9) present the case 2, 36 m high building for the time instant 24s and 72s respectively. These figures show the rooms on the 4th. and 10th. floors with grave smoke contamination due the closed end on the top of the inflow air duct.

Figure 8. Case 2 - double duct: air inflow/exhaust smoke construction, partícles on 24 s, 36 m building.

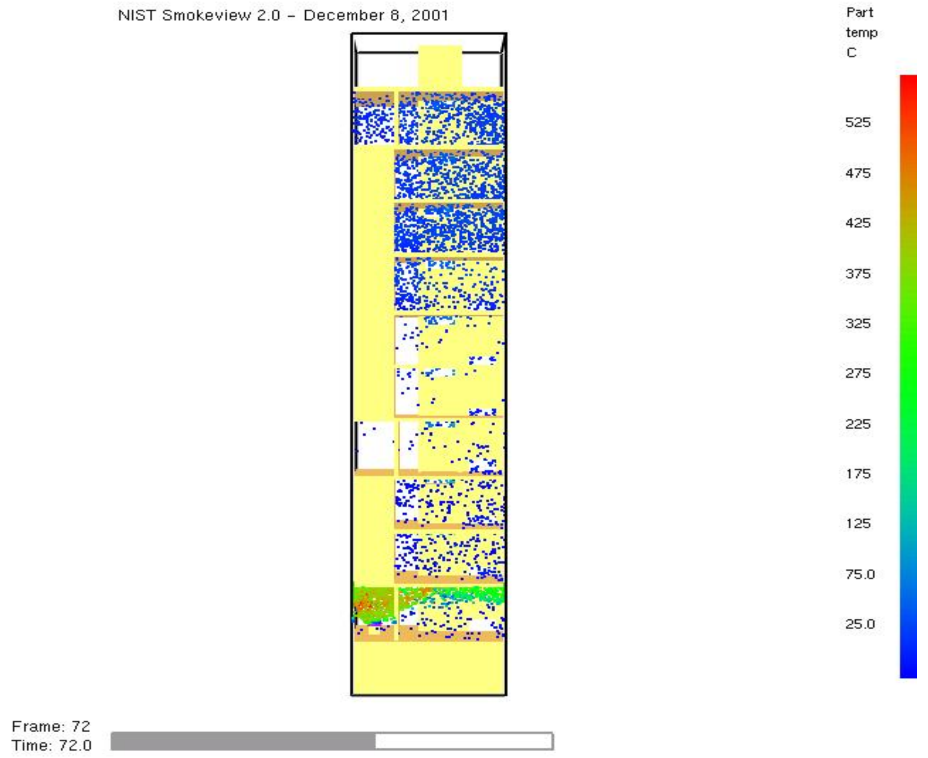

Figure 9. Case 2 - double duct: air inflow/exhaust smoke construction, partícles on 72 s, 36 m building.

6. Conclusions

In the present work, the effectiveness of natural ventilated ducts to protect emergency staircases was investigated. There were simulated two design concepts of natural ventilated smoke ducts. The influence of the height was investigated by simulating buildings of 18 m and 36 m. The fire focus is on 1st. floor of the buildings. The temporary evolution of the smoke contamination for 4th. and 10th. floors are compared. From the obtained results, it can be concluded that case 1 - single duct building - showed a better effectiveness to avoid the smoke contamination in the staircase and upstairs compartments of the building. This conclusion is valid for both low and high buildings. This investigation is very important for Fire Brigades and Fire-Safety Designers in Brazil. This work, using a complex model, stresses the conclusions obtained by (Vittorino, 1998), who uses the zone model for smoke movement.

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