AIR CURTAINS TO REDUCE FIRE SMOKE POLLUTION

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ABSTRACT

This theoretical paper studies of the interaction between air curtains system and purging dilution systems in a real urban underground railway station in order to find the best design to reduce concentration of polluting gas toward adjoining environments.
Numerical computations are carried out with NIST package Fire Dynamics Simulator (FDS). The use of an approximate form of the Navier-Stokes equations for low Mach number application is appropriate. Polluted gasses flow towards safe space can be reduced of the 26-53% by operating air curtain systems.

INTRODUCTION

Smoke management includes all methods that can modify smoke movement to protect occupants and fire fighters,and to reduce property damage. Barriers, smoke vents and shaft, supplying and exhausting large quantities (purging dilution) of air in space in which the fire is located, are traditionally used. Doors in conjunction with air flow and pressure differences generated by mechanical fans are a very common system in smoke control, as the only smoke purging is unable to provided the needed air flow at the open doors and pressure differences across barriers. In many practical applications escape routes towards refuge areas are not equipped with doors, especially in large common-space. In this last case the use of air curtains, with the function of barrier, could be useful in reducing or delaying smoke infiltration toward escape ways. Atria in commercial multi-stories buildings, exhibition halls, sports arenas, railway stations are typical examples of large commonplaces that present such problem.
While there are a lot of works and guidelines (NFPA 1995 [1], Klote and Milke 1992 [2], Tamura 1995 [3], Yamana and Tanaka 1985 [4], Hansell and Morgan 1994 [5]), standards and codes (BOCA 1996 [6], NBCC 1995 [7], CEA-4020 1999 [8], UNI-9494 1989 [9]) devoted to the design of smoke controls, air curtains do not find a lot of considerations as smoke barriers. Besides preliminary studies about air flow rates and pressure fields analyses produced by air curtain systems can be find in Gugliermetti and Santarpia [10, 11, 12]

This paper present a theoretical study of the interaction of air curtains and purging diluition systems in a real urban underground railway station in order to find the best design to reduce concentration of polluting gas in environments near to the place in which the fire is set.
Numerical computations are carried out with the NIST package Fire Dynamics Simulator, FDS (McGrattan & alt. 2000/1 [13], 2000/2 [14]), which use an approximate form of the Navier-Stokes equations appropriate for low Mach number application (Rehm and Baum, 1978 [15]). The computation is treated in this paper as a Large Eddy Simulation (LES), in which the large scale eddies are computed directly and the sub-grid scale dissipative process are properly modeled.

Combustion in a LES approach can't be calculated directly, as it is occurring at length scale below the numerical grid; the fire is then represented by Lagrangian particles (thermal elements) that originate at solid surface and release heat at a specified rate. The thermal elements and the LES approach provide a self-consistent description of the smoke transport at all resolvable length and time scale and produce faster numerical calculations and more manageable models respect to the Direct Numerical Simulation (DNS) and respect to reactive kinetic approaches.

CALCULATION HYPOTHESYS

The studied two adjoining spaces are reported in Figures 1 and 2; they are the schematisation of a real urban underground railway. The first space (called Atmosphere 1) and the second one (called Atmosphere 2) are connected with a 2.0 x 2.1 m door opening; an air curtain system is installed above the door at a height of 2.1 m from the floor; it supplies 1.2 m^2/s of outdoor air by 2.0 x 0.2 m free area grille. In the Atmosphere 1 there is the train dock and a lower zone in which the train runs, entering and getting off the space through two openings of 3 x 3 m each (called Tunnels).

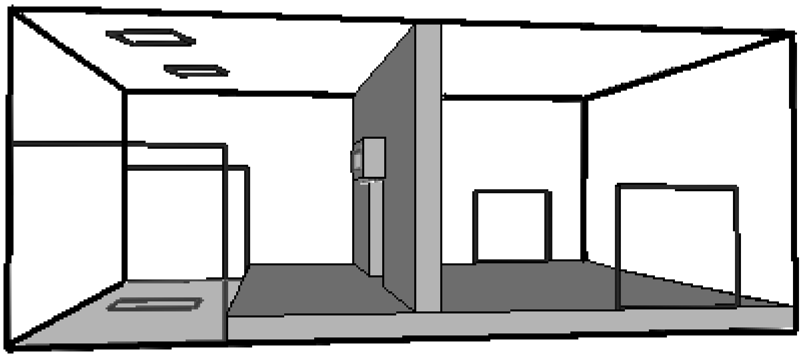

Figure 1: Simulation domain geometry

Atmosphere 2 (9 x 6 x 4.6 m) has two openings towards the outdoor called "Openings" (2 x 2 meters each) (the atria of the subway station).
Two 1.2 x 1.2 m free area exhaust air ceiling grilles are considered to operate either in Atmosphere 1 or in Atmosphere 2; in this case air flow rate is 1.5-2 m^2/s for each grill with a mean speed turns 1-1.3 m/s.

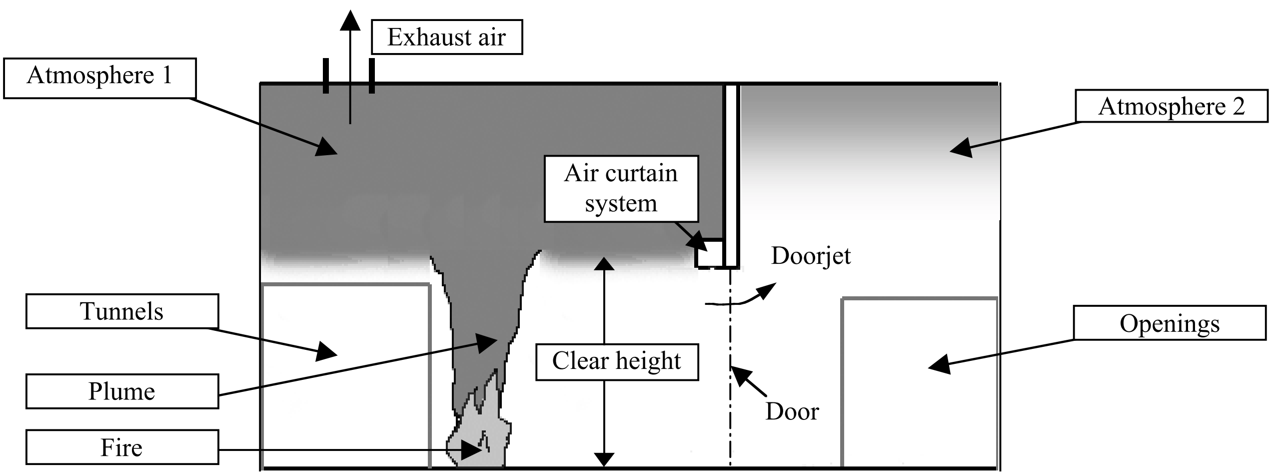

Figure 2: Zone model idealization of a room fire

The Openings and the Tunnels are defined like "OPEN" in the simulation package. The number of grid cells is 44 x 59 x 24 and each cell is 20.45 x 20.24 x 20.83 cm.
Initial air temperature in Atmosphere 1 and Atmosphere 2 is 15ºC. The external walls and the inner walls are considered INERT (adiabatic) and they temperature is constant at 15 ºC. The fire heat release rate (HRR) is 450 kW on fire surface of approximately 2 m^2 (that is 208,3 kW/m^2) and is produced by propane combustion (49000 kJ/kg). Convective HRR is assumed to be the 70% of the total heat released. The considered combustion gaseous species are Nitrogen, Oxygen, and Carbon dioxide. Air composition is 72 % nitrogen, 28% oxygen. The CO_2 production rate is 3 kg for every kg of burnt propane.
Gas concentration, relative pressure and air flow are calculated in prefixed points in which virtual probes are settled. CO_2, pressure and flow rate probes are settled in a vertical array with step of 1m in Atmosphere 1 and Atmosphere 2 (with the exclusion of the zones occupied by the plume), in 0.20 x 0.20m rectangular array near the door and the exhaust air grille, in 0.30 x 0.30m rectangular array in the Tunnels.
All simulations are extended till to 120 s from the beginning of the fire.

RESULTS

Four different cases of purging dilution systems have been analysed: 1) Exhaust system flow rate from Atmosphere 1 of 3 m^2/s, 2) Exhaust system flow rate from Atmosphere 1 of 4 m^2/s, 3) Exhaust system flow rate from Atmosphere 2 of 4 m^2/s, 4) No exhaust system flow rate.
In the first and the second case an exhaust smoke layer, whose thickness is respectively 1.60m and 2.30m., is produced in Atmosphere 1.
CO_2 concentration and air temperature for the case 1 are reported in Figures 3 and 4.
Air mass flow ratse on the "Door", "Tunnels", "Openings" and the mass balance for the case 1 are represented respectively in Figures 5 and 6, 7 and 8, 9 and 10.
The cumulative mass CO_2 flow rate through the door for all the nconsidered cases is reported in Table 1, after 120 s of simulation.

TABLE 1
Total mass of CO_2 through the door [kg]

Conditions of extraction	Air curtain OFF	Air curtain ON	Variation	Variation %
1) Extraction 3 m^2/s from Atmosphere 1	4,05 x 10^{-2}	4,34 x 10^{-2}	0,29 x 10^{-2}	7 %
2) Extraction 4 m^2/s from Atmosphere 1	2,5 x 10^{-2}	3,4 x 10^{-2}	0,9 x 10^{-2}	36 %
3) Extraction 4 m^2/s from Atmosphere 2	20,7 x 10^{-2}	15,4 x 10^{-2}	-5,3 x 10^{-2}	-26 %
4) No extraction	18,9 x 10^{-2}	8,9 x 10^{-2}	-10,0 x 10^{-2}	-53 %

CO_2 flow is always from Atmosphere 1 to 2, both with the air curtains swithched ON and OFF; the CO_2 flux is $3.38x10^{-4}$ kg/s with air curtain OFF and rise to $3.62x10^{-4}$ kg/s when air curtain system is ON (see Table 2).
On the contrary local over-pressure, due to the air curtain, reduces the movement of air masses from Atmosphere 1 to Atmosphere 2. The smoke, also if diluited by the external clean air, flows to Atmosphere 2 and produce pollution (figure 11,12).

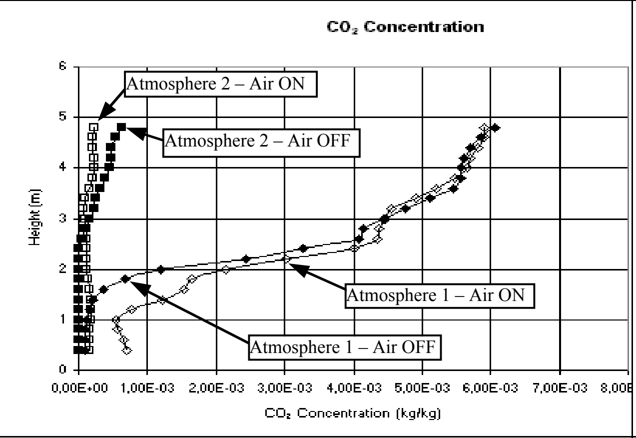

Figure 3: Case 1 - CO_2 concentration.

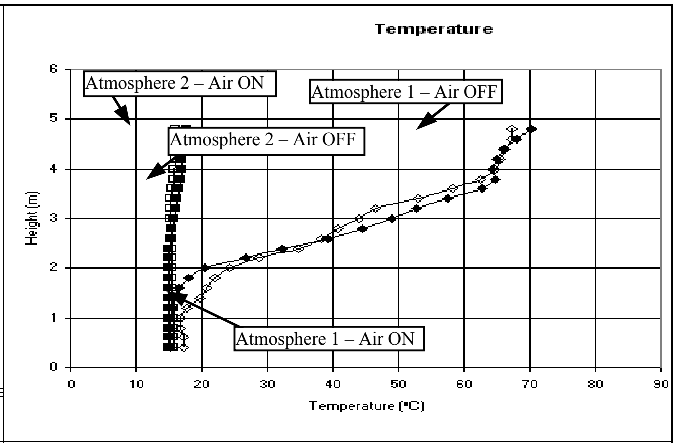

Figure 4: Case 1 - Temperature.

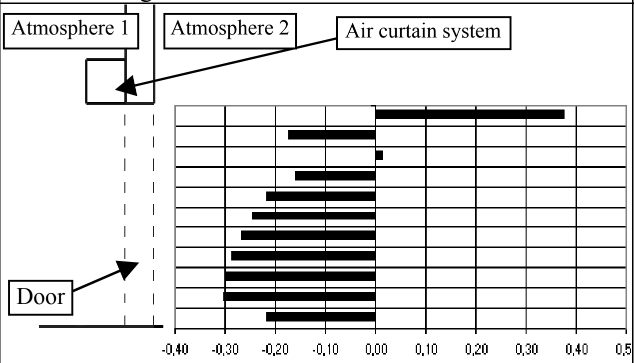

Figure 5: Mass flux (kg/s) (air curtain OFF)

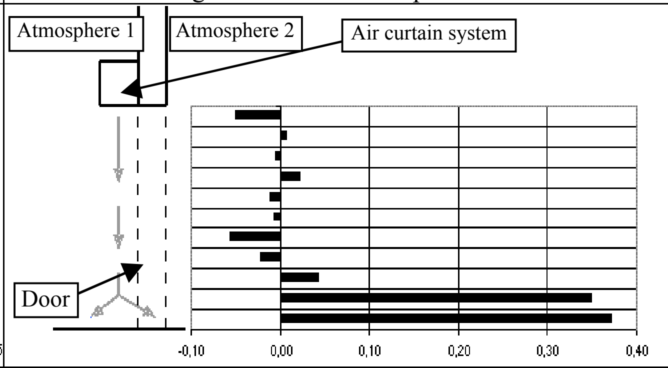

Figure 6: Mass flux (kg/s) (air curtain ON)

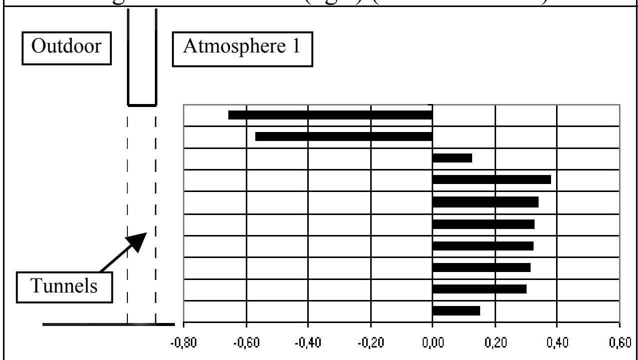

Figure 7: Mass flux (kg/s) (air curtain OFF)

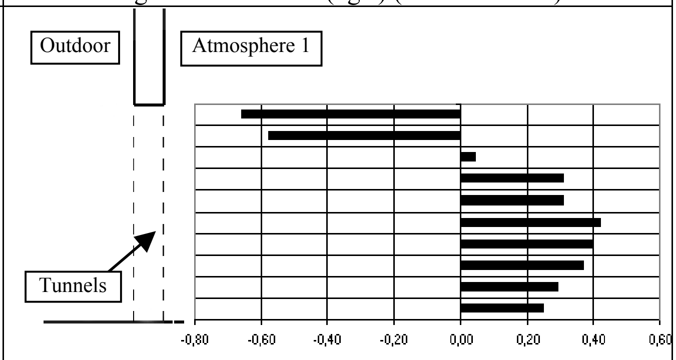

Figure 8: Mass flux (kg/s) (air curtain ON)

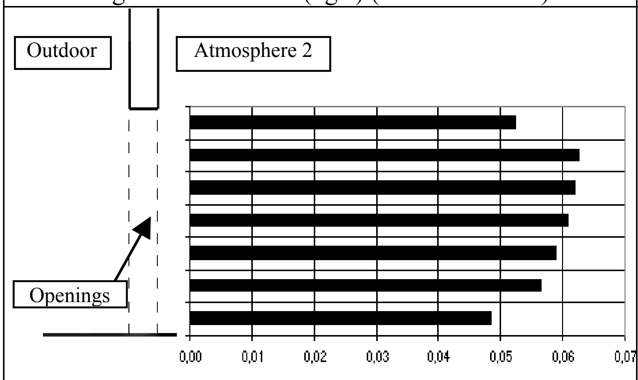

Figure 9: Mass flux (kg/s) (air curtain OFF)

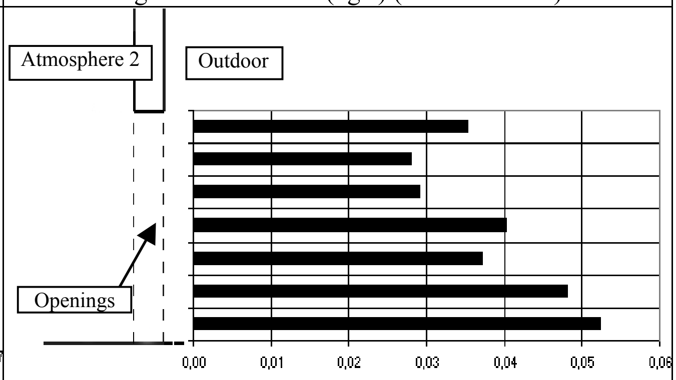

Figure 10: Mass flux (kg/s) (air curtain ON)

CO_2 data concentrationsand temperature are reported respectively in Table 3 and Table 4 for the smoke layer and the clear height for all the considered cases.
In the first case, when air curtain system is OFF in Atmosphere 1 the CO_2 concentration is 5.3×10^{-3} (kg CO_2/kg air) (Table 3); in the clear air zone is approximately 1×10^{-4} (kg CO_2/kg

air). In Atmosphere 2 there is a stratification, but CO_2 values are unappreciable: 5 x 10^{-4} (kg CO_2/kg air) for the upper zone, and small traces in the lower zone. With air curtain ON, in Atmosphere 1 there is 5.4 x 10^{-3} kg CO_2/kg air in the upper zone and 7 x 10^{-4} kg CO_2/kg air in the lower zone. Atmosphere 2 becomes sufficiently mixed that it is impossible to define a true stratification, and can be considered all at the same concentration, that is approximately near to 2 x 10^{-4} kg CO_2/kg air.

TABLE 2

CO_2 mass flow on the connecting door [kg/s]

Conditions of extraction	Air curtain OFF	Air curtain ON	Variation	Variation %
Case 1 - Extraction 3 m^2/s from Atmosphere 1	3,38 x 10^{-4}	3,62 x 10^{-4}	0,24 x 10^{-4}	7 %
Case 2 -Extraction 4 m^2/s from Atmosphere 1	2,08 x 10^{-4}	2,83 x 10^{-4}	0,75 x 10^{-4}	36 %
Case 3 - Extraction 4 m^2/s from Atmosphere 2	17,25 x 10^{-4}	12,83 x 10^{-4}	-4,42 x 10^{-4}	-26 %
Case 4 - No extraction	15,75 x 10^{-4}	7,42 x 10^{-4}	-8,33 x 10^{-2}	-53 %

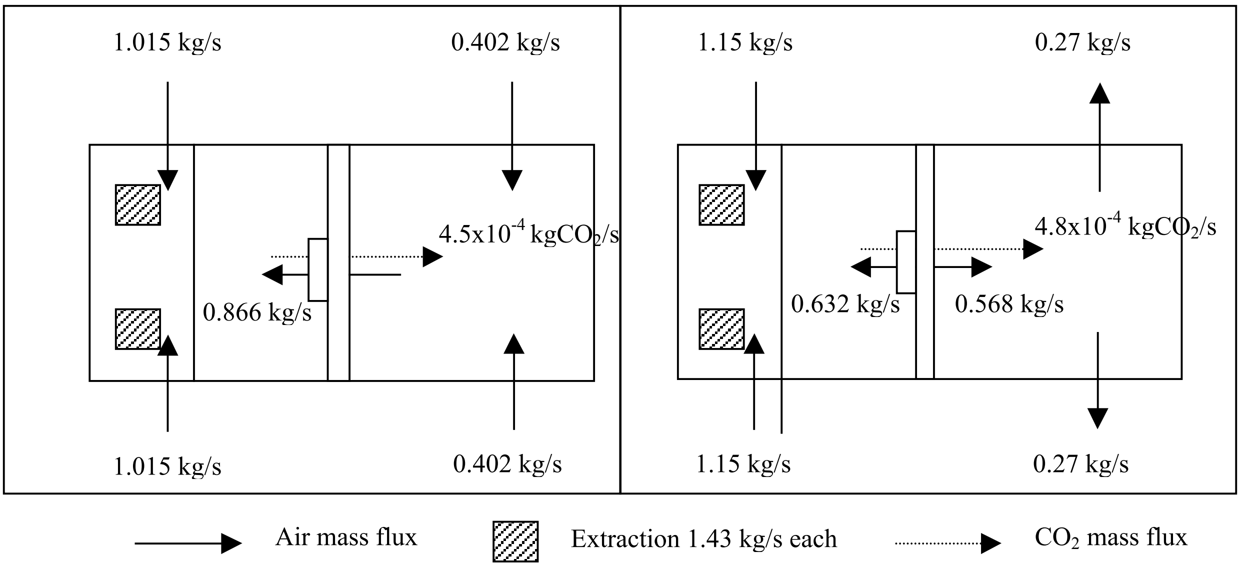

Figure 11 - Balance of mass flux (air curtain OFF) Figure 12 - Balance of mass flux (air curtain ON)

TABLE 3

CO_2 concentration after 120 second (kg CO_2/kg aria)

	Air curtain system	Atmosphere 1		Atmosphere 2	
		In the smoke layer	In the clear height	In the smoke layer	In the clear height
Case 1)	OFF	5.3 x 10^{-3}	1 x 10^{-4}	5 x 10^{-4}	
	ON	5.4 x 10^{-3}	7 x 10^{-4}	2 x 10^{-4}	2 x 10^{-4}
Case 2)	OFF	4.2 x10^{-3}	1 x 10^{-4}	2 x 10^{-4}	
	ON	4.3 x 10^{-3}	6 x 10^{-4}	1 x 10^{-4}	1 x 10^{-4}
Case 3)	OFF	6.5 x10^{-3}	6 x 10^{-4}	1.1 x 10^{-4}	
	ON	6.5 x 10^{-3}	5 x 10^{-4}	5 x 10^{-4}	5 x 10^{-4}
Case 4)	OFF	6.5 x10^{-3}	6 x 10^{-4}	1.2 x 10^{-4}	
	ON	6.5 x 10^{-3}	8 x 10^{-4}	5 x 10^{-4}	5 x 10^{-4}

In Atmosphere 1 there is a remarkable thermal stratification with a mean smoke temperature of 65 ºC, and of 17ºC in the lower zone. Atmosphere 2 is less subject to space temperature variations; when air system turned OFF a vertical temperature gradient is more appreciable (Table 4).

TABLE 4
Temperature after 120 second (ºC)

	Air curtain system	Atmosphere 1		Atmosphere 2	
		In the smoke layer	In the clear height	In the smoke layer	In the clear height
Case 1)	OFF	65	15	17	15
	ON	65	18	16	16
Case 2)	OFF	52	15	17	15
	ON	52	18	16	16
Case 3)	OFF	75	18	20	15
	ON	76	21	17	17
Case 4)	OFF	75	18	21	15
	ON	78	19	18	18

CONCLUSION

If air curtain is system operating with external air immission, and air purge extraction system is turned off, high efficacy to reduce CO_2 outlet flux (-53%) is allowed (Table 2, case 4). If fan extraction system is turned ON then an airflow across the door, toward the Atmosphere 1 where extraction openings are placed, is induced.
Viceversa pollution flow through the separation door, when the air extraction purge system is on and when it is not placed in the pollution source zone (Atmosphere 2), can be reduced (-26%, case 3);
To the contrary, an exhaust flow purge system operating in the same space where the fire is developed (case 1 and 2), can guarantee people safety and the use of air curtain can increase by 7÷36% the smoke flow rates towards adjoining environments (Table 2).
The air curtain system supplies outddor air to both zones Atmosphere 1 and Atmosphere 2, thus following that it can be installed within either Atmosphere 1 or 2.
Numerical simulation results have shown that it is more advisable to set "on" the air extraction purge system that pertains to the inddor spaces wherein the fire develops. In the same time the air curtain system must be shut "off".

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