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Experimental analysis of a plume dispersion around obstacles

S. Brusca[a], F. Famoso[b]*, R. Lanzafameb, A. Marino Cugno Garrano[b], P. Monforte[b]

[a]*University of Messina, C.da Di Dio, Messina 98166, Italy*
[b]*University of Catania, V.le A. Doria 6, Catania 95125, Italy*

Abstract

Nowadays, transport and deposition of aerosol particles ($PM_{2.5}$, PM_{10}, TSP) caused by industrial plants, environmental applications and transports, are of great concern to public health. Despite the establishment by the European Union of emission standards (European directive 2008/50/CE e.g) to control the limits of particulates in the air, the emissions by industrial plants are still not accurately monitored. In particular, the interaction between plume dispersion and obstacles, such as buildings, is not currently well studied. A lot of theoretical researches were carried out in this field with a lack of experimental data comparison. This paper focuses on a laboratory work made to better explain the interaction of a continuous plume released from a point source and various obstacles. First of all a vertical pipe was reproduced, a continuous aerosol emitter was characterized in terms of a specified and controlled mass flow and the ratio between smoke emission and the total suspended particulates thanks to use of the certified gravimetric calculation of PM_{10}. The experimental campaigns were conducted by means of a wind tunnel all the data collected were validated. The characterization of plume was made by the use of several sensors and calculation of velocity in several points of the field. Moreover, the plume dispersion was studied also by using digital image analysis. It was then investigated downwind the influence of obstacles of various shapes and distances from source in terms of aerosol concentration in several points.

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Keywords: aerosol particles, image processing, ANOVA, emissions.

* Corresponding author. Tel.: +39 095 7382455.
E-mail address: ffamoso@unict.it.

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1. Introduction

In response to an increasing concern for environmental issues especially about air quality in cities, many scientific works have been carried out about air pollution dispersion models during last decades.

Chemical species and pollutants have various emission pathways into the atmosphere. They can be emitted from several sources: point sources (e.g industrial plant chimneys, volcanic eruptions, accidental release at nuclear power plants), line sources (e.g motorways) or area sources (emissions of photochemical smog precursors and forest fires). The deposition, transport and interaction with buildings or obstacles of particles are possible to be modelled in several ways.

Many studies about pollution dispersion models have been focused on large scale environments [1, 2]. In these cases, when obstacles or buildings dimensions are insignificant in comparison with the dispersing plume cross-section, usually conventional dispersion models, such as Gaussian models [3, 4] or Lagrangian models [5, 6] are used to simulate the flows and dispersion patters.

The interaction of continuous plume released from point sources with buildings and other structures is the mayor factor affecting short-range dispersion of atmospheric pollutants in urban areas. In these cases, the use or some field studies and wind tunnel experiments is necessary to better explain this interaction [7]. Usually, in these cases, an important characteristic of the flow is the formation of one or more vortexes generated near the ground upwind of the obstacle effecting considerably the shape of the flow and the concentrations downwind [8]. This paper investigates on an experimental study about a continuous emission point source of particulate matters and its interaction with different obstacles at different distances in a wind tunnel chamber.

Nomenclature

L	Height of the emitter [mm]
D	Diameter of the emitter outlet [mm]
$\dot{m}_{PM10}$	Mass flow of PM_{10} [μg/s]
v_e	Emitter outlet velocity [m/s]
v_w	Wind tunnel velocity [m/s]

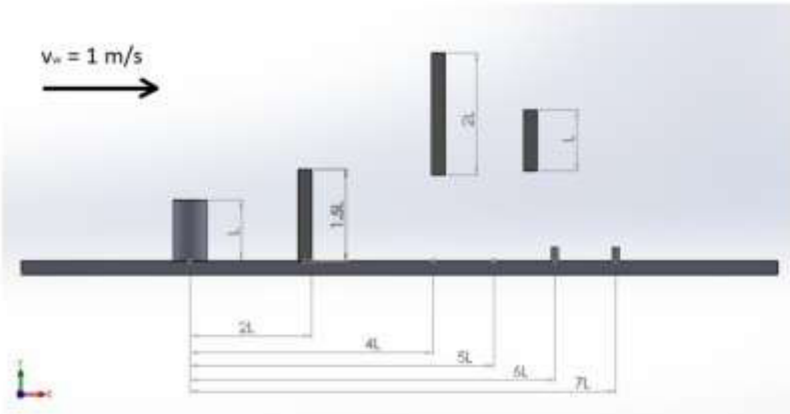
2. Experimental set up and methods

Wind tunnel experiments were conduced in the laboratories of the Industrial Engineering Department of University of Catania. The wind tunnel has test chamber 500 mm high, 500 mm wide and 1130 mm long. A detailed description of the wind tunnel is provided by Brusca et al. [9]. It was built a wood case fitting exactly in chamber test of the wind tunnel. In this case it was placed an emitter and three sensors for PM_{10} concentrations in three different positions. Aerocet-531S Mass Particle Counters were used as sensors. All elements of the case were downwind and the velocity of the approach flow was always 1 m/s. A continuous aerosol emitter of cylinder shape as point source was used. The burning incense was characterized in terms of mass flow and velocity outlet. Several tests were conduced and it was used the certified gravimetric calculation of PM_{10}. The results of them were similar especially in terms of the relation between smoke emission and the total suspended particulates; they were also confirmed in [10, 11]. Tab. 1 shows the details of the emitter.

Table 1. Emitter main characteristics.

Emitter details	Value
L	90 mm
D	20 mm
V	0,6 m/s
$\dot{m}_{PM10}$	15,6 μg/s

There were used three different obstacles, all of them with the same thickness (20 mm) and width (260 mm). Their heights were chosen in proportion with the height of the emitter: H_1=L, H_2=1,5L, H_3=2L. Each test was characterized by the use of one obstacle at a time. They were placed in three different positions, also the distances of these points from the emitter were considered in proportion with L: 2L, 4L, 5L. The sensors (S1, S2, S3) were placed always in the same positions. Fig. 1 shows the experimental configuration, the two suspended obstacles are shown just to understand the proportions.



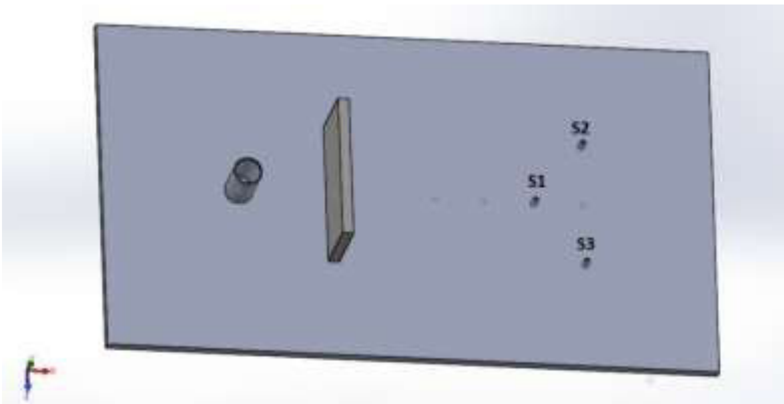


Fig. 1. Experimental set up with its components.

There were nine possible configurations in terms of Distance of the obstacles from the emitter and their heights. For each configuration the test was reproduced 5 times for a total of 45 tests plus a set of 5 tests for the experiment without obstacles that was used as comparison to better understand the incidence of the obstacles. In each test there was first calculated the background PM_{10} in order to consider only the contribution of the aerosol emitter. Each test was validated and for each configuration, given that there were not a great variation of results, the PM_{10} concentration average for each sensor was taken. The results were treated by two-ways and one-way *analysis of Variance (ANOVA)*. The heights of obstacles and their distances from the emitter were used as factors in order to know if there was a relation with the concentrations in the three sensors. The exterior boundaries of plume were also analyzed using some algorithms in image processing. For each test performed, 600 images were treated. Avarage pixel intensity was calculated for all images acquired. Thus, the average boundary was obtained. Firstly contrast was enhanced in all images. Secondly images were converted to black and white (binary image) in order to prepare for boundary tracing using a specific algorithm able to detect edges in images [12].

3. Results

The results from *Anova* are shown in Tab. 2. Both one-way analysis, considering distance and heights separately, and two-ways, considering the interaction between them, demonstrate that these factors are significant for the concentration in all sensors (P < α-level in all cases). Moreover, the coefficient of determination is very high in all cases (R^2 > 80%), demonstrating that the variation in the response is explained very well by the model.

Table 2. Anova analysis results.

		DF	SS	MS	F_{calc}	P	α-level	R^2 [%]	$R^2_{(adj)}$ [%]
S1	***Distance***	2	397338	198669	12.06	0.000	0.005	92.27	90.89
	Height	2	3559373	1779686	108.04	0.000			
	Interaction	4	4887072	1221768	74.17	0.000			
	Error	45	741246	16472					
	Total	53	9585028						
S2	***Distance***	2	74502	37251	11.21	0.000	0.005	83.82	80.94
	Height	2	225878	112939	34.00	0.000			
	Interaction	4	473681	118420	35.65	0.000			
	Error	45	149474	3322					
	Total	53	953535						
S3	***Distance***	2	65909	32954	10.94	0.000	0.005	92.01	90.59
	Height	2	635568	317784	105.47	0.000			
	Interaction	4	860237	215059	71.38	0.000			
	Error	45	135580	3013					
	Total	53	1697294						

As shown in fig. 2, the trend of PM_{10} concentrations is not the same for all configurations. Whenever the obstacle was placed in position 2L or 4L there is an increase of PM_{10} concentrations in each sensor in relation with the heights of obstacles. For the position 5L the results are opposite: as the obstacle is higher as the concentrations are lower in all sensors. Probably the presence of vortexes caused by the obstacles tends to move the plume farer from the source. In the case of 5L, the position closest to the sensors, the masking effect is probably stronger than the contribution of turbulent structures.

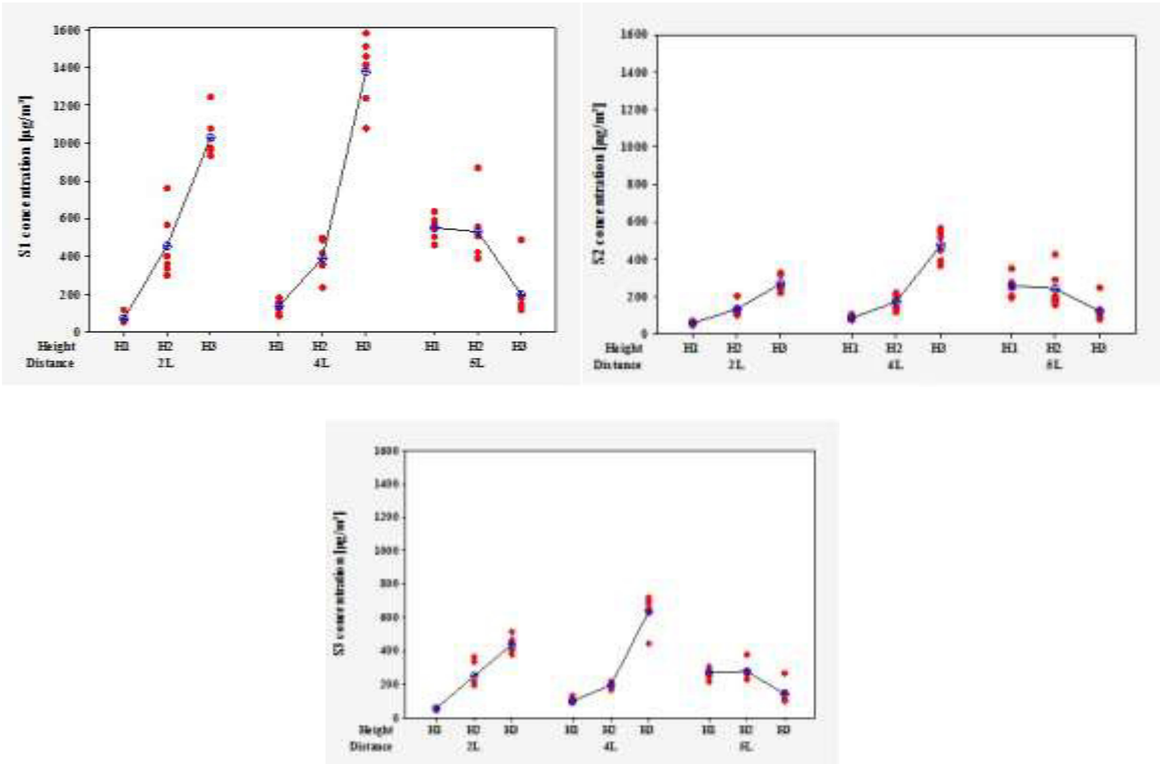


Fig. 2. Concentrations of PM_{10} in S1, S2 and S3 for all configurations.

Tab. 3 shows, as it was demonstrated before, how the obstacles amplified the concentration of PM_{10} for almost all configurations. Thanks to some image analysis algorithms and the conversion of pixels in mm (Image scale factor), it was possible to quantify the contribution of the obstacle in terms of the difference between the peak of the plume without obstacle and the peak with it referring it to the height of the obstacle. For configuration in Fig. 3, i.e Δpeak = 0,37 H_2 with Image scale factor = 6,8 pixel/mm.

Table 3. Ratio between mean Concentration Values for all sensors (S1, S2 and S3) and the Mean Concentration values without obstacles (S1', S2', S3') for all configurations.

		H_1	H_2	H_3
$\frac{S1}{S1'}$	*2L*	**0,29**	1,90	4,30
	4L	**0,57**	1,64	5,78
	5L	2,31	2,22	**0,84**
$\frac{S2}{S2'}$	*2L*	1,15	2,73	5,45
	4L	1,75	3,49	9,59
	5L	5,21	4,89	2,49
$\frac{S3}{S3'}$	*2L*	**0,96**	4,53	7,86
	4L	1,80	3,48	11,47
	5L	4,86	4,96	2,51

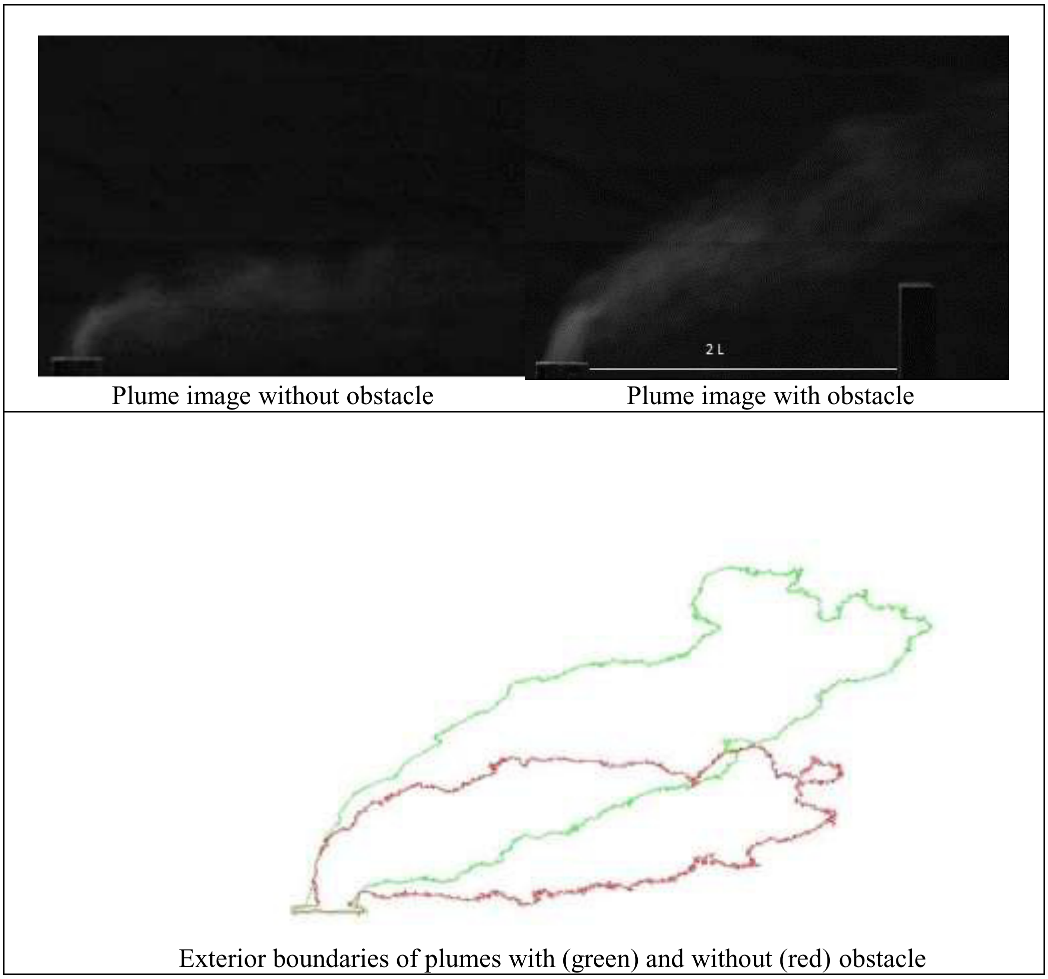


Fig. 3. Image analysis for the configuration with obstacle with H_2 and distance 2L.

4. Conclusions and future works

The correlation between plume from point source and obstacles with different shapes and in different positions was investigated in this work. It was conduced the analysis of variance and the results highlighted especially how the vortexes on the bottom of the obstacles amplified the concentration of aerosol particles beyond the obstacles. It was then determined the necessary distance from the source to obstacles so as the PM_{10} could decrease. The image analysis procedure allowed to visualize the profile of the plume when there were or not obstacles. Also by this analysis it was highlighted how the plume without obstacles reached higher peaks. For future work it is under analysis the idea to use image processing to better define the plume shape and above all to define inversion layers and their relation with obstacles. It is also under analysis the idea to use image processing to associate aerosol particles concentrations with pixel densities.

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Biography

Fabio Famoso received the M.Sc. degree in Computing Engineering at the University of Catania in 2007. He received the Ph.D at the University of Catania in 2011. He is currently working at the Industrial Engineering Department of the University of Catania as research fellow since 2012. His current research interests focus on the renewable energies and environmental monitoring systems.