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Theoretical and experimental study of Gaussian Plume model in small scale system

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Abstract

Atmospheric dispersion pollution modelling is of great and actual concern in the scientific international community. Many dispersion models have been developed and used to estimate the downwind ambient concentration of air pollutants from sources such as industrial plants, vehicular traffic or accidental chemical release. Among them, Gaussian model is perhaps the most commonly used model type. It is often used to predict the dispersion of air pollution plumes originated from ground-level or elevated sources. In this research an experimental campaign was carried out in the wind tunnel of the Industrial Engineering Department of University of Catania. It was tested an emission plume of particulate matters and the concentrations of PM_{10} were evaluated in several points downwind beyond the emitter. Both the wind velocity and PM_{10} mass flow were varied in order to test the differences in terms of PM10 concentrations in the sampling points. A Gaussian plume mathematical model was developed according the boundaries conditions of the experimental campaign. The results of the model were compared with experimental ones in order to identify the limits and the advantages of this model in such a small scale system.

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Keywords: air pollution, dispersion model, aerosol particles, wind tunnel.

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1. Introduction

The dispersion of air pollution both in urban areas and open spaces is becoming of great concern in the scientific community. In last decades the normal levels of air pollution have increased [1] and many countries have started to focus to develop monitoring systems for air pollution. With the European directive 2008/50/CE all European countries have declared to adopt a standardized way to control, monitor and study air pollutants in urban areas. In such scenario, many air quality models to predict, study and evaluate the pollution dispersion have been studied and implemented [2]. Air quality models are able to predict the pollutant gases or aerosol trajectories in atmosphere. Generally, these pollutants cab be emitted by industrial sources [3], hazard chemical released due to accidents or natural events [4], and vehicular urban traffic [5, 6]. The evaluation and calibration of dispersion models is of a crucial importance, because their results often influence decisions that have large public-health and economic consequences. Obviously there are different types of models and their performances depend on many variables. The classification of these models may refer about the source type (point source, line source, area source), the adopted scale (large or small scale), the input type (deterministic models and stochastic models), the dynamic conditions (steady or unsteady state), the pollutant sources (gases or particles). Many reviews [7, 8] have already classified and studied these models, trying to focus about performance in respect with the variables stated before. Among all these possible models the most used are probably Lagrangian and Gaussian models. Both of them are able to estimate the downwind ambient concentration of air pollutants from different sources types. Lagrangian models work well both for homogeneous and stationary conditions over the flat terrain [9] and unstable media condition for the complex terrain [10] but they usually suffer for computational calculation and they cannot be used for real time applications. Gaussian models are widely used in atmospheric dispersion modelling, usually in regulatory purposes because of their easy implementation and their near real-time responds. They generally are used in large scale applications [11] and although they have been shown to over-predict concentrations in low wind conditions [12], since the plume models are calculated with steady state approximations they do not take into account the time required for the pollutant to move from the source to the receptor. In this research a Gaussian plume model was implemented and tested in small scale scenario thanks to experimental campaigns carried out in a wind tunnel. The performances of this model in such a small scale set up were then studied by comparing model results with experimental ones.

Nomenclature

L	Height of the emitter [mm]
D	Diameter of the emitter outlet [mm]
$\dot{m}_{PM10}$	Mass flow rate of PM_{10} [μg/s]
C_{PM10}	PM_{10} concentration [μg/m^3]
V_e	Emitter outlet velocity [m/s]
U	Wind tunnel velocity [m/s]

2. Gaussian Plume Model

The greatest advantage of Gaussian Plume models is that they have an extremely fast, almost immediate response time. Their calculation is based only on solving a single formula for every receptor point, and the model's computational cost mainly consists of meteorological data pre-processing and turbulence parameterization. Depending on the complexity of these sub-modules, the model's runtime can be extremely reduced enabling its application in real-time and near real-time decision support software. Gaussian dispersion models have become a uniquely efficient tool of air quality management for the past decades, especially in the early years when high performance computers had an unreachable price for environmental protection organizations and authorities. Their fast responds depend basically on several assumptions that make them useful for just some applications. The main important assumptions are:

- The emission rate of the source is constant;

- Dispersion (diffusion) is negligible in the downwind direction;
- Horizontal meteorological conditions are homogeneous over the space modeled. For each step modeled:
  a) Wind speed is constant
  b) Wind direction is constant
  c) Temperature is constant
  d) Mixing height is constant
- No wind sheer in the horizontal or vertical plane;
- The pollutants are non-reactive gases or aerosol;
- The plume is reflected at the surface with no deposition or reaction with the surface;
- The dispersion in the crosswind and vertical direction take the form of Gaussian distributions.

The sources types may be different: point source, volume source, area source, open pit and flare. Usually it is possible to implement Gaussian models for more than one source and as assumption it is considered the Superposition principle. The Gaussian plume adopted in this work was implemented in MATLAB® and is described as follow. First of all, an orthogonal Cartesian reference system is assumed with its origin corresponding to base position of the source and the x axis parallel to the wind direction. The y axis horizontal and perpendicular to the x axis while the z axis in vertical direction corresponding to the height from the ground direction. The concentration C(x,y,z) in any point is described by the following equation:

$$C(x,y,z)=\frac{\mathrm{Q}}{2\pi\sigma_y\sigma_z\mathrm{U}}\cdot exp\left(-\frac{y^2}{2\sigma_y^2}\right)\cdot\frac{1}{\sqrt{2\pi\sigma_z}}exp\left[-\frac{(z-L)^2}{2\sigma_z^2}\right] \quad (1)$$

The two Gaussian exponential functions are normalized respect to the maximum value and describe the dispersion degree of the plume in horizontal and vertical direction. L is the height of the emitter. U is the wind velocity at height of the barycentre of the hypothetical plume. Q is the mass flow rate. The width of the plume is determined by σ_y and σ_z which are defined by atmospheric stability classes [13, 14]. In the implemented model these two coefficients were calculated with a novel way. A Genetic Algorithm was used to determine constants stability coefficients for small scale particulate dispersion system.

3. Experimental set up and model implementation

Wind tunnel experiments were conduced in the laboratories of the Industrial Engineering Department of University of Catania. It was used almost the same experimental set up of [15]. It was used a wood case fitting the chamber test of the wind tunnel. An aerosol continuous emitter and three sensors (S1, S2, S3) for PM_{10} were placed in the positions showed in Fig. 1 and 2.These sensors were placed at positions whose distance from the emitter was multiple of its height L. Aerocet-531S Mass Particle Counters were used as sensors to survey C_{PM10}. A continuous aerosol emitter of cylinder shape as point source was used. The velocity of the approach flow U, always orthogonal to the emitter, was varied from 1 m/s to 5 m/s with a step of 1 m/s. The mass flow rate $\dot{m}_{PM10}$ of the emitter was varied from 10 [µg/s] to 20 [µg/s]. The main characteristics of the Experimental set up are show in Tab. 1.

Table 1. Set up main characteristics.

Emitter details	Value
L	90 mm
D	20 mm
V_e	0,6 m/s
$\dot{m}_{PM10}$	10 and 20 µg/s
U	1, 2, 3, 4 and 5 m/s

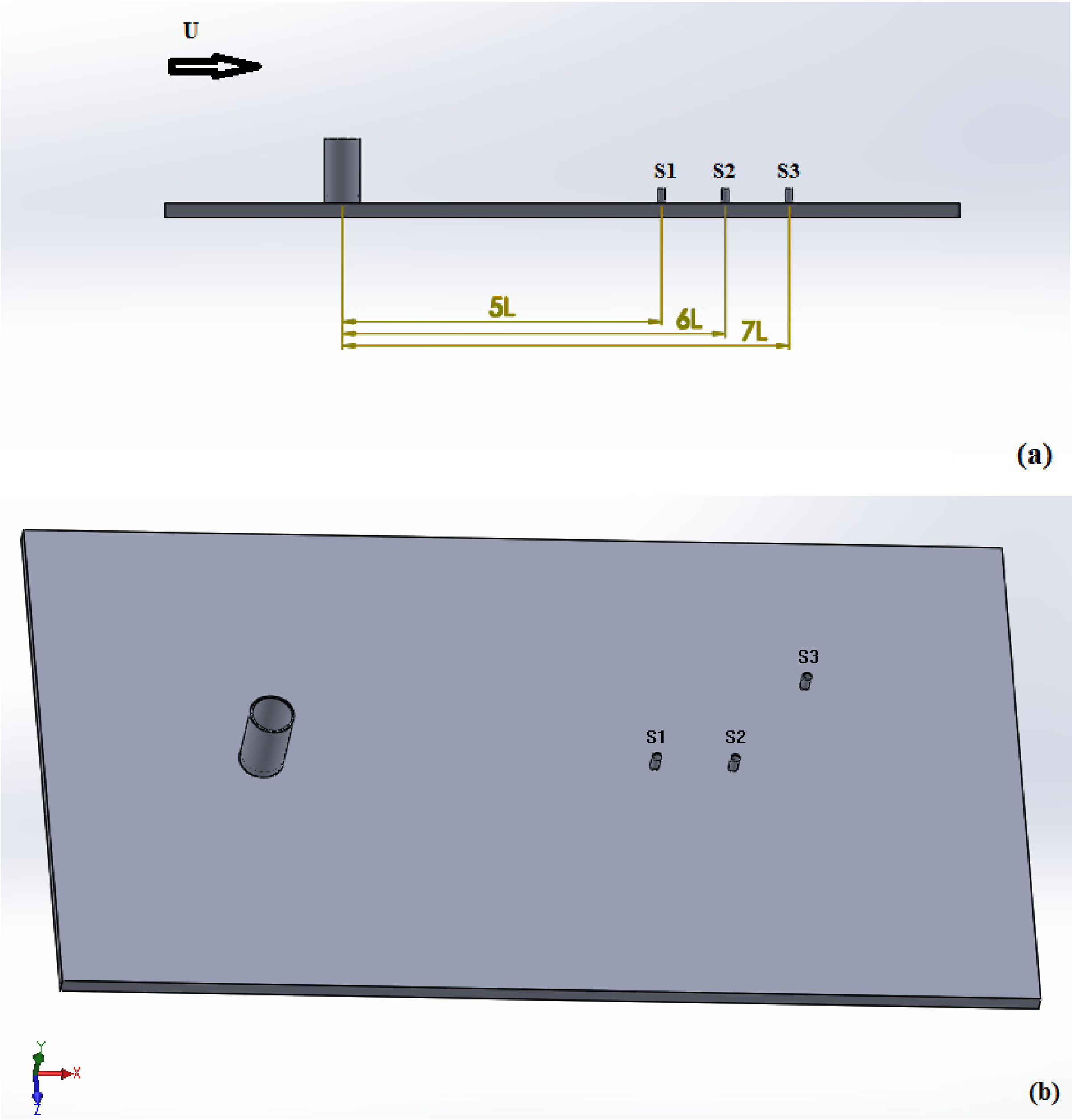

Fig. 1. (a) Lateral view of wood case with distances and U direction; (b) Plan view of sensors configuration.

There were 10 possible configurations in terms of U and $\dot{m}_{PM10.}$ For each configuration the test was reproduced 5 times for a total of 50 test. In each test there was first calculated the background C_{PM10} in order to consider only the aerosol emitter contribution. The results were treated by one-way and two-way analysis of Variance (ANOVA). Anova demonstrated that each test did not present a great variance in terms of C_{PM10} in all sensors so it was consider only the average. Moreover The two-way analysis, considering U and $\dot{m}_{PM10}$ as factors, demonstrated that these factors are significant for all C_{PM10} in all sensors. In the Gaussian model there were set the following variables:

- Wind field without any turbulent fluctuation
- Wind velocities according experimental values
- Mass flow rates Q according experimental values
- Number of sources set at 1 (*stacks = ONE_STACK*)
- Heights of emitter and sensors
- C_{PM10} calculated in 2D (considering the plane x-y)
- Source coordinates
- The grid calculation dimensions were set as the wood case of Fig. 1
- Reference system origin was set in in the lower left corner of the grid

Fig. 2. Picture of the experimental set up.

4. Results

First of all experimental results were treated separately. As shown in Fig. 3 it is possible to see S1, S2 and S3 C_{PM10} at varying U and $\dot{m}_{PM10}$. These results show how the C_{PM10} varies proportionally with the $\dot{m}_{PM10}$ in all three sensors. The slope of this variation is almost the same for S1 and S3 while in S2, where there are the highest C_{PM10} values, the slope is greater. Moreover the distance in terms of C_{PM10} tends to decrease with the increase of U in all sensors.

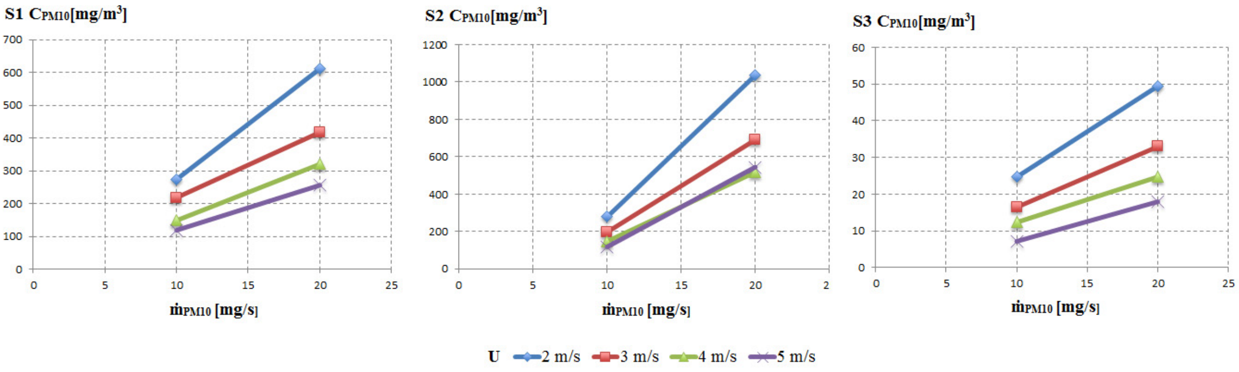

Fig. 3. Experimental results for S1, S2 and S3.

The model implemented gave good results as shown in Tab 2. The error varied from 0,10 % to 6,79 %. The best results were found where U= 2 m/s while the worst results where generally found where U = 4 m/s. Fig. 4, 5, and 6 shows how the model fits with experimental results in all sensors.

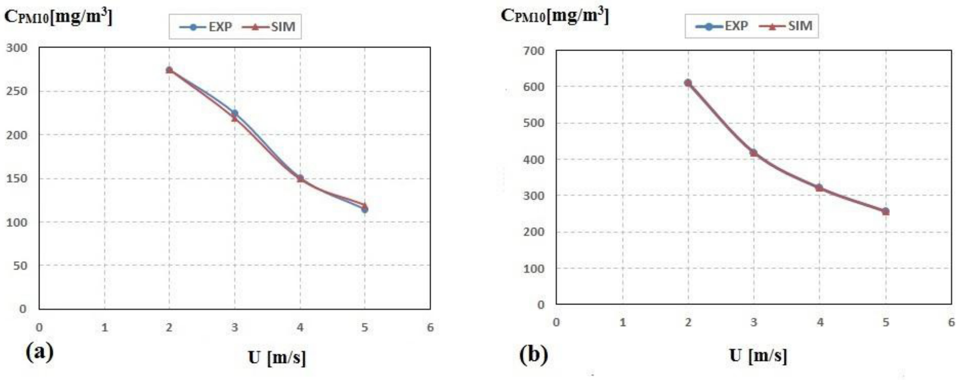

Fig. 4. (a) S1 results comparison with $\dot{m}_{PM10}$=10 [μg/s] (b) S1 results comparison with $\dot{m}_{PM10}$=20 [μg/s].

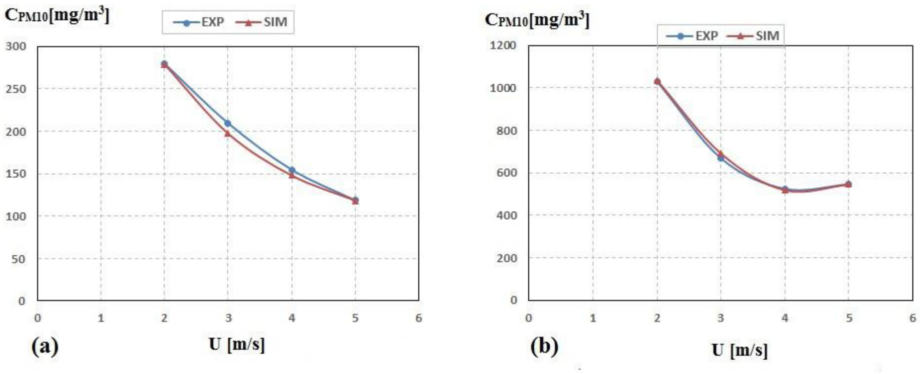

Fig. 5. (a) S2 results comparison with $\dot{m}_{PM10}$=10 [μg/s] (b) S2 results comparison with $\dot{m}_{PM10}$=20 [μg/s].

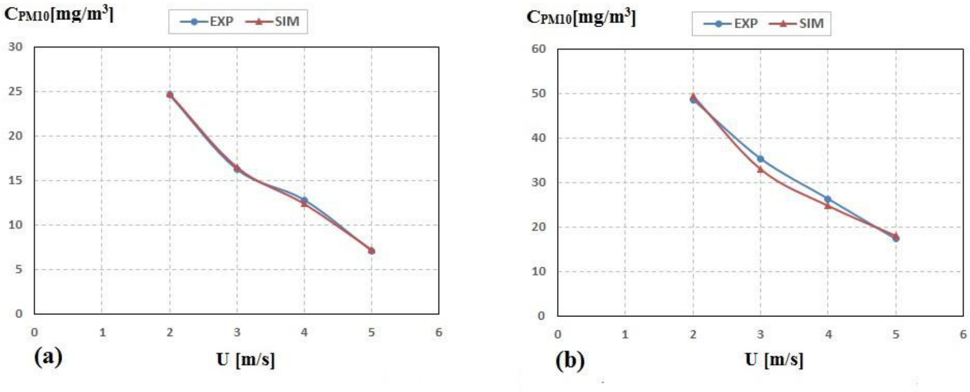

Fig. 6. (a) S3 results comparison with $\dot{m}_{PM10}$=10 [µg/s] (b) S3 results comparison with $\dot{m}_{PM10}$=20 [µg/s].

Table 2. Numerical and experimental results in all possible configurations.

			WIND TUNNEL SPEED (U)			
			2 m/s	***3 m/s***	***4 m/s***	***5 m/s***
S1	**$\dot{m}_{PM10}$ 10µg/s**	*Experimental C_{PM10} [µg/m^3]*	274,90	224,79	150,90	114,55
		Numerical C_{PM10} [µg/m^3]	274,62	218,90	149,25	119,40
		Error [%]	**0,10**	**2,62**	**1,09**	**4,23**
	$\dot{m}_{PM10}$ 20 µg/s	*Experimental C_{PM10} [µg/m^3]*	608,84	418,21	320,57	256,65
		Numerical C_{PM10} [µg/m^3]	611,93	417,90	320,89	256,71
		Error [%]	**0,51**	**0,07**	**0,10**	**0,02**
S2	**$\dot{m}_{PM10}$ 10 µg/s**	*Experimental C_{PM10} [µg/m^3]*	279,81	209,56	154,82	118,70
		Numerical C_{PM10} [µg/m^3]	278,87	197,35	148,01	118,41
		Error [%]	**0,34**	**5,82**	**4,40**	**0,24**
	$\dot{m}_{PM10}$ 20 µg/s	*Experimental C_{PM10} [µg/m^3]*	1031,92	668,33	524,84	546,39
		Numerical C_{PM10} [µg/m^3]	1036,10	690,70	518,10	544,70
		Error [%]	**0,40**	**3,35**	**1,29**	**0,31**
S3	**$\dot{m}_{PM10}$ 10 µg/s**	*Experimental C_{PM10} [µg/m^3]*	24,62	16,25	12,81	7,08
		Numerical C_{PM10} [µg/m^3]	24,72	16,48	12,36	7,19
		Error [%]	**0,41**	**1,41**	**3,50**	**1,55**
	$\dot{m}_{PM10}$ 20 µg/s	*Experimental C_{PM10} [µg/m^3]*	48,64	35,36	26,29	17,27
		Numerical C_{PM10} [µg/m^3]	49,44	32,96	24,72	17,98
		Error [%]	**1,66**	**6,79**	**5,98**	**4,08**

5. Conclusions

This paper focuses on the implementation of a Gaussian plume model to analyze and study PM_{10} dispersion in a small scale system. An experimental set up in a wind tunnel was used to validate this model. Results revealed that performances of the model were quite robust at varying of wind velocity and mass flow outlet. The error was always less than 7% in all configurations. The near real-time nature of this model makes it a good tool for regulatory purpose.

The results of this controlled environment could be extended to real scale phenomena by facing a deeper analysis of meteorological variables in order to find solution when turbulence conditions occur. This model could be also easily used as objective function in optimization algorithms (e.g. genetic algorithms) used in reversing methods to separate and identify pollutants sources.

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