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MODEL FOR CONTROL OF INDOOR AIR QUALITY IN AN INDUSTRIAL ENVIRONMENT*

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Abstract. This paper is focused on indoor air quality study (IAQ) into a metallurgic industrial hall. A model (named INPOLL) for computing the time evolution of concentrations of various air pollutants in closed working areas was carried out. The model uses a partition of the working unit in a convenient number of cells with known transfer and ventilation air fluxes. The hall is also supposed to communicate with its exterior, both by accidental air leakages and through the ventilation system. Then, a time-dependent injection of pollutants occurring in various sites of the working space determines the subsequent evolution of pollutant concentrations in all the compartments of the partition. Starting from some given set of background concentrations, the model can predict the values of the pollutant concentrations in each cell, at any time from the start. Maxima of pollutant concentrations result when some furnace begins the discharging process. By varying the model parameters (like the air currents for ventilation or the time delay between furnace discharges), one can obtain a process optimization from the point of view pollutant concentrations. The model is suitable for dynamic simulations of indoor environmental dispersion of pollutants.

Key words: indoor model, indoor pollution, industrial working space.

1. INTRODUCTION

Indoor air quality is a problem of any program dealing with safe industry practices and with the control of air pollution [1, 2, 3]. The continuous need for highly productive industrial units brought in the legitimate demand of increased security of the personnel in the working places. It is an area of concern for, because

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improperly designed ventilation systems lead to significant health risk exposures through inhalation hazards, as well as energy inefficiencies, which increase the overhead costs of an industrial operation. We developed a model to simulate the dynamics of indoor pollutant concentrations. The computational model can be used to optimize the operation of a multiple-furnace metallurgical unit in terms of the overall concentrations of related gaseous pollutants [4, 5]. The modeling can replace the *in situ* measurements and it offers significant pollution prevention opportunities through capturing of energy credits, in increasing the productivity of workers through improved comfort, reducing waist of time from illness and injury, reducing medical costs by minimizing or eliminating inhalation hazards, and reducing facility insurance premiums by providing a safer work environment [6, 7].

In order to evaluate the relevance of the contribution of the indoor to the overall exposure of the personnel by inhalation, the study included the indoor pollutant variability associated with the different heights of flats above the ground level. Therefore, in the second section, a few theoretical considerations are presented, including a brief description of the model. In the third section, some illustrative results obtained by using the model are presented and in section four, the validation of the model is discussed. The last section presents the conclusions.

2. BRIEF DESCRIPTION OF THE MODEL

The working space (hall) is divided in a suitable number of cells (C1, C2, C3…..C20) communicating with each other and with the exterior by specified air fluxes and leakages, respectively (Fig.1). A ventilation system is considered to force the air outwards through suitable filters [8]. The furnaces are placed in line, at the lowest level in the hall. Each furnace is supposed to have a complex operation cycle consisting of charging, heating and discharging. The Indoor Pollution model (INPOLL) considers the homogeneous chemistry, without reaction affecting the transport of gas-phase pollutants like sulfur dioxides or carbon monoxide indoors. The mathematical model is developed and applied to predict indoor pollutant concentrations resulting from the furnace discharging and transport. Also the integral expressions used to estimate the model parameters are presented [2, 9].

The time variation of the pollutant production can be suitably modeled and the source intensities are considered as input data [2]. The corresponding pollutant production is considered significant only during the discharging phase.

Eq.1, a time-dependent balance equation, is integrated numerically to obtain the pollutant concentrations in each cell. Maxima of pollutant concentrations result when some furnace begins the discharging process.

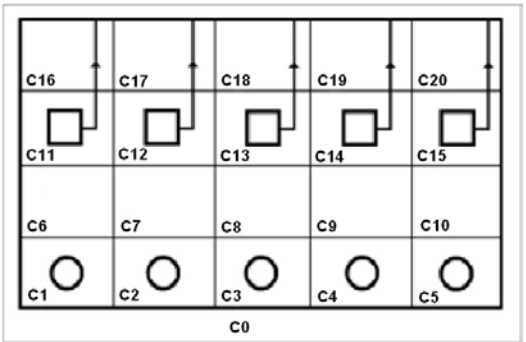

Fig. 1 – Scheme of the working space with five furnaces. The circle represent outlet of discharges of each furnace; the rectangles represent the units of the ventilation system. The exterior (assigned with the index zero) is considered as a separate cell with a constant background pollutant concentration.

$$V_{cel}\frac{\mathrm{d}C}{\mathrm{d}t} = S(t) - L(t)C, \tag{1}$$

where: C is the pollutant concentration in a cell; $S(t)$ is the corresponding source term of pollutant, in the cell (kg/s); $L(t)$ describes the variation of the pollutant concentration in the cell due to the advections to and from its neighbors. For the inert chemical compounds, the effects of diffusion and ventilation system are introduced in the equation (2):

$$\frac{\mathrm{d}C_i}{\mathrm{d}t} = \sum_{j=o}^{n}\left[\frac{f_{ji}C_j - f_{ij}C_i}{V_i}\right] + \left[\frac{f_{xl}C_x - f_{ix}C_i}{V_i}\right] - \frac{\eta_{ii}f_{ii}C_i}{V_i}, \tag{2}$$

where*:* C_i , is the pollutant concentration in a cell i ;V_i – the volume of the cell *i,* f_{ij} – the flow rate (m^3/s) from cell *i* to cell *j,* η_{ij} – the retention efficiencies of pollutant on the filter.

As the index *x* is related to the ventilation system and the index "0" *for* the outdoor air, one may write:

$$C_x = \frac{\sum_{j=0}^{n}(1-\eta_{jx})f_{jx}C_j}{\sum_{j=0}^{n}f_{xj}}, \tag{3}$$

where C_x is pollutant concentration at level of ventilation system.

The source terms have been chosen of Gaussian type:

$$S(t) = \frac{S_{\max}}{\sqrt{2\pi\sigma}}\exp\left[-\frac{(t-t_m)}{2\sigma^2}\right], \tag{4}$$

where σ = 1 min, t_m = 5 min, and $S_{max} = 12\times10^3$ mg/min. All these parameters are computed and they represent the input data of the model. The discharging time is 30 minutes and the furnace starts a new discharging after approximately 180 minutes.

Optimal operation regimes can be obtained by varying functional parameters (like ventilation fluxes or the time delay between furnace discharges).

3. RESULTS AND DISCUSSIONS

3.1. MEASURED DATA

The measurements were made into a real industrial space, called in paper as the hall, in a few campaigns between years 2003 and 2005. We take those from June 2004 as input data for the model. The gaseous pollutant measurements were carried out using portable equipment, MX 21 PLUS, which incorporates a self-diagnostic function that indicates any irregularities in its operation thereby providing complete confidence in the measurement. The multi-gas type MX 21 PLUS can simultaneously detect the presence and extent of up to four gases [12]. It was used to determine the mass concentration of the following chemical agents at work: CO, SO_2, and NO_2.

This equipment has an adequate measuring interval for the mentioned pollutants: CO (0-351) mg/m^3, SO_2 (0–80) mg/m^3 NO_2 (0–58) mg/m^3 (for the temperature range from –20°C to +50°C and relative humidity between 10% – 95%). The admissible legal limits of gas concentrations for 15 minutes exposure are the following: for NO_2, 8 mg/m^3; for CO, 30 mg/m^3; for SO_2, 10 mg/m^3 [11]. The indoor micro-climate has been measured with Casella Microtherm Heat Stress Monitor and Testo 435.

Our studies have shown that the values of the NO_x concentration are constant and small during the discharging phase (Table 1, Fig. 2). Therefore, we have insisted on carbon monoxide and sulfur dioxide as gaseous pollutants.

The model was applied for the workspace of a metallurgical unit with five furnaces. In addition, the pollution was simulated for a single furnace.

The model works as a box-type one, but with possible air communication between the five furnaces and with four vertical levels where personnel may be placed: 4m, 8m, 16m and 20m (Table1, Fig. 2). At the last level, there are filters for gases and total suspended particles.

Table 1

Mean concentration values for 30 min (discharging time) at furnace C3

Measuring point and period	**NO2 (mg/m^3)**	**CO (mg/m^3)**	**SO_2 (mg/m^3)**
LEVEL 0m, before discharging	0.96	1.16	1.34
LEVEL 4m ,during discharging	2.62	10.10	7.75
LEVEL 8m, during discharging	2.29	3.04	3.02
LEVEL 16m, during discharging	1.6	2.92	2.04
LEVEL 20m, during discharging	1.28	1.53	1.72

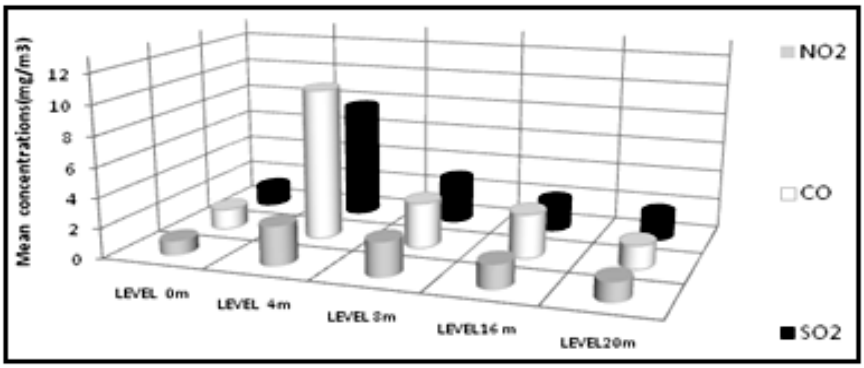

Fig. 2 – Mean concentration values for 30 min at C3.

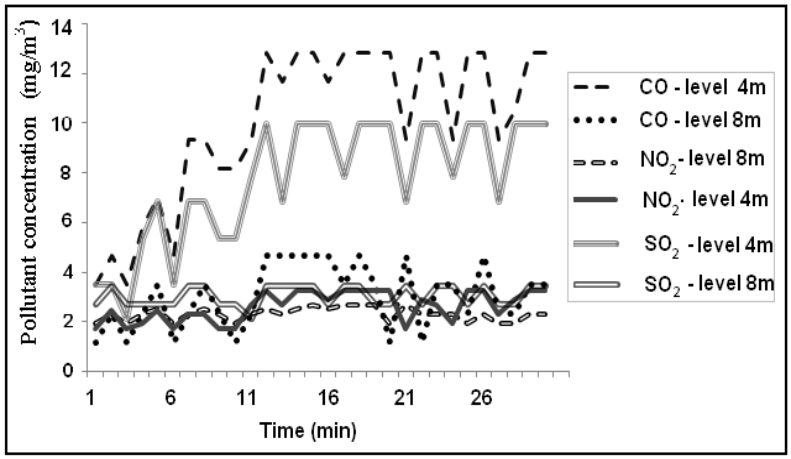

Fig. 3 – Temporal averaged concentration of pollutants for furnace C3, at levels 4m and 8m.

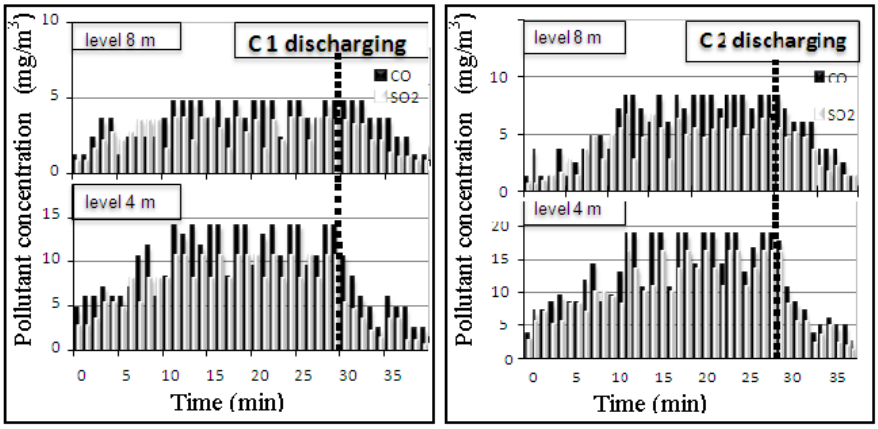

Fig. 4 – Time evolution of the sulfur dioxide and carbon monoxide concentrations of furnaces C1 and C2.

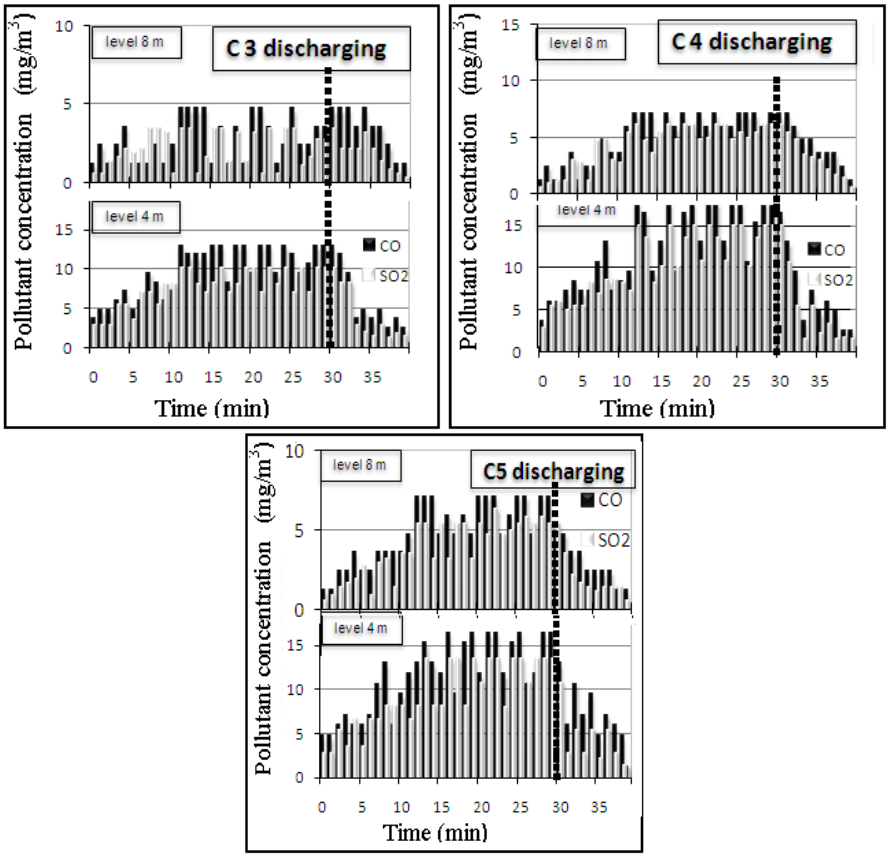

Fig. 5 – Time evolution of the sulfur dioxide and carbon monoxide concentrations of furnaces C3, C4, C5 in time of discharging.

In Figs. 4 and 5 the temporal evolutions of the gaseous pollutants sulfur dioxide and carbon monoxide of furnaces C1-C5 are shown. One can observe the maximum concentration values during the enhanced discharging. The mean time for intense discharging is between 10 and 15 minutes.

Measurements of CO and SO_2 at levels between 4 m and 8 m at the furnaces C1-C5 revealed the following facts:

At the level of 4 m higher values of the concentrations than at the level of 8 m have been detected, with the highest concentrations in the lines of C4 and C2.

Following the analysis of the data shown in Figs. 4, 5 one can observe a rise of pollutant concentration between the tenth and the thirtieth minute of the discharging phase. As this phase ends after 30 minutes, the concentration levels of the pollutants begin to decrease.

At the level of 8 m, after 30 minutes, a slow decrease of the concentrations is noticed, looking almost as a plateau. At the same time, measurements at 4 m show a fluctuating behavior due to the strong air currents that interfere with the pollutant dispersion. These differences between the levels of 4 m and 8 m are also visible at the beginning of the discharging phase.

The relatively low levels of the CO concentrations are due to the technological flow used in the metallurgical unit that involves no carbon-based reduction processes. The existing CO is apparently generated by the graphite electrodes used to electrolytically decompose the ore.

The inside meteorological parameters of the industrial hall have been determined at all levels and their vertical variations are shown in Figs. 6 and 7. One can observe important changes in temperature and relative humidity when the furnaces operate: the temperatures become very large and the relative humidity very small, as expected.

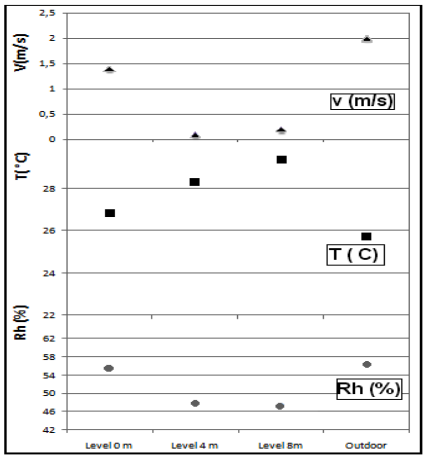

Fig. 6 – The vertical distribution of the relative humidity, temperature and air flow for the columns of level 0 m, level 4 m, level 8 m outdoor (outside)– (don't furnaces operated).

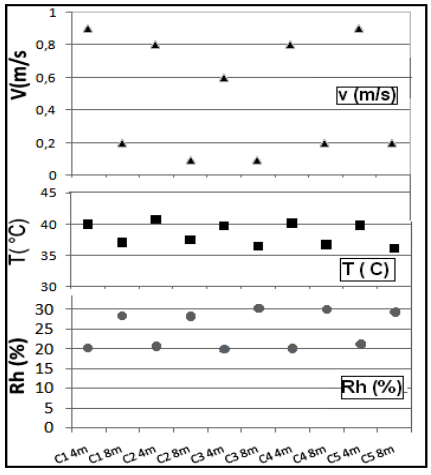

Fig. 7 – The vertical distribution of the relative humidity, temperature and air flow for the columns of furnaces C1, C2, C3, C4, C5 during the discharging.

So, higher temperatures, lower humidity and higher speed of air currents have been measured at the level of 4 m as compared to the level of 8 m.

The analysis of the dispersion rate of gaseous pollutants shows that, generally, 65% of it is dispersed toward the upper levels. Consequently, the pollutants from each furnace influence the neighboring areas.

3.2. RESULTS OBTAINED BY USING THE MODEL

The model was applied in many situations but here we illustrate a particular simulated case with five operating furnaces (Fig. 8). The time variation of pollutant concentrations in the working area of furnaces is presented. For technological reasons, the furnaces do not operate simultaneously.

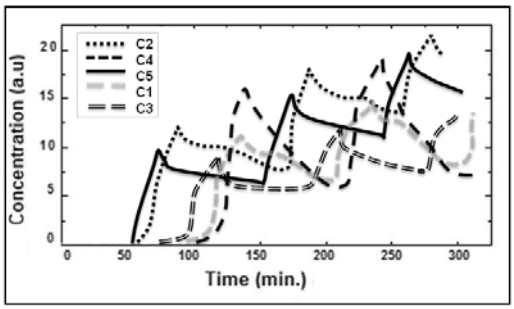

Fig. 8 – Time evolution of a gaseous pollutant concentration in the working area of furnaces C1-C5. As the ventilation efficiency was insufficient, a steady average built-up of the pollutant in the area is observed.

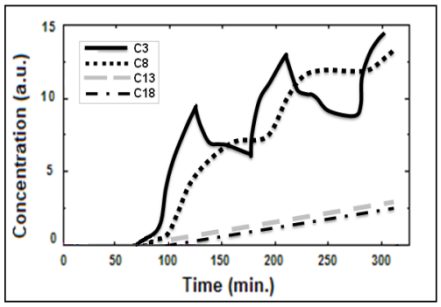

Fig. 9 – Time evolution of gaseous pollutant concentrations on the vertical: cells C3, C8, C13 and C18 in the same conditions as for Fig. 8.

There is a certain delay in the operation cycles of every adjacent couple of them, Δt . Therefore, the periodical increases in the amount of pollutant correspond to the discharging episodes of each furnace. Reciprocal influences due to air currents appear as secondary maxima on some of the diagrams. As the ventilation was set at insufficient values, an overall accumulation of pollutant is visible in all areas as an average increase of the concentrations with time.

In Fig. 9 the same example is illustrated on the vertical of the third furnace. At the ground level the curve is identical to the one in Fig. 8. The periodical variations in concentration fade out at the next level and disappear completely in the highest cells, where the pollutant accumulation is weaker.

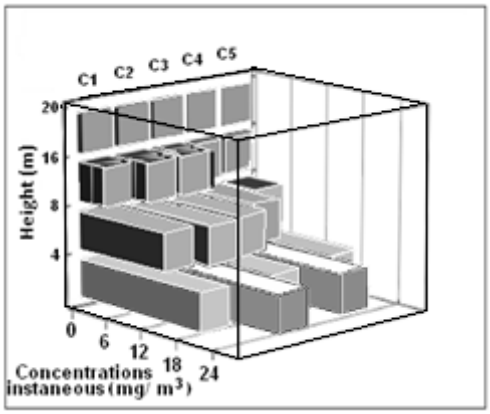

Fig. 10 – Instantaneous concentration in the metallurgical unit after 130 minutes since the operation was started.

The significant reduced concentration along the vertical is explained by both the horizontal dispersion of pollutants and as an effect of the ventilation system.

The model provides also global instantaneous values of pollutant concentrations in the work area at any instant during the operation. Figure 10 shows a possible representation of the concentration values after 130 min from the general turn on of the unit. Each bar corresponds to a cell in the space of the hall. The bar lengths and color represent the concentration levels. Generally, at lower levels the concentrations are higher than at the upper ones. At the considered instance, maximum values are at the outlets of furnaces C2 and C4. These two furnaces have higher productivity than C1 and C3 due to a recent upgrade. This simulated result is validated by measured values (Figs. 4 and 5). As expected, the ventilation and evacuation systems determine rather low levels of concentration in the upper cells.

4. **EXPERIMENTAL VALIDATION OF THE MODEL**

The usual statistics was applied for model validation. In addition, the normalized bias and normalized sigma (standard deviation) were computed [10]:

$$f_b = \frac{1}{0.5}\frac{\overline{C}_0 - \overline{C}_p}{\overline{C}_0 + \overline{C}_p} \quad \left(\text{normalized bias}\right);$$

$$f_s = \frac{\sigma_0 - \sigma_p}{0.5(\sigma_0 + \sigma_p)} \quad \left(\text{normalized standard deviation}\right),$$

where

$\overline{C}_0 = \frac{\sum_{i=1,n} C_i}{n}$ represents the average value, $\sigma = \sqrt{\frac{\sum_{i=1}^{n} \left(C_i - \overline{C}_0\right)^2}{n-1}}$ – the standard deviation, and $\overline{C}_0 - \overline{C}_p$, the *bias*. $\overline{C}_0$ and $\overline{C}_p$ are average measured and computed concentrations, respectively.

Table 2

Statistical parameters for validating the INPOLL model

SO_2 -C1 (time of discharging)							
SO2	**Level (as in Fig1)**	**Mean (mg/m^3)**	**Sigma (mg/m^3)**	**Bias (mg/m^3)**	f_b	f_s	**Correlation coefficient %**
Measured values	C1.	8.67	6,40	0	0	0	1
	C6.	6.90	4.11	0	0	0	1
Computed values	C1.	8.87	5.51	- 0.197	-0.024	0.149	0.68
	C6.	5.71	3.55	1.187	0.188	0.146	0.57

The values in Table 2 show that the specific indicators are in normal uncertainty limits, validating the model capacity to provide concentration values comparable with the measured ones.

Figures 11 and 12 show sample results of model computations (continuous lines) compared to measured concentrations (histograms) of SO_2 and CO near two of the furnaces of a real unit. The rather close correlation between calculated and measured data has been obtained by varying technological parameters (*e.g.* ventilation fluxes, source strengths, time gap between discharges etc.) and exchange fluxes between neighboring cells. Some of these parameters have been measured and the corresponding values have been used in computations. The fitting was performed with the undetermined variables. It can be seen that the average concentration of each gaseous pollutant keeps a steady value, with the sulfur dioxide tendency to accumulate near the ground level and a reverse trend for carbon monoxide. Once the fitting parameters determined, they have been used for computing concentrations at any cell of the working space. Moreover, varying some technological parameters one can find optimal operation regimes that both maximize the productivity and minimize the hazard exposure of the people.

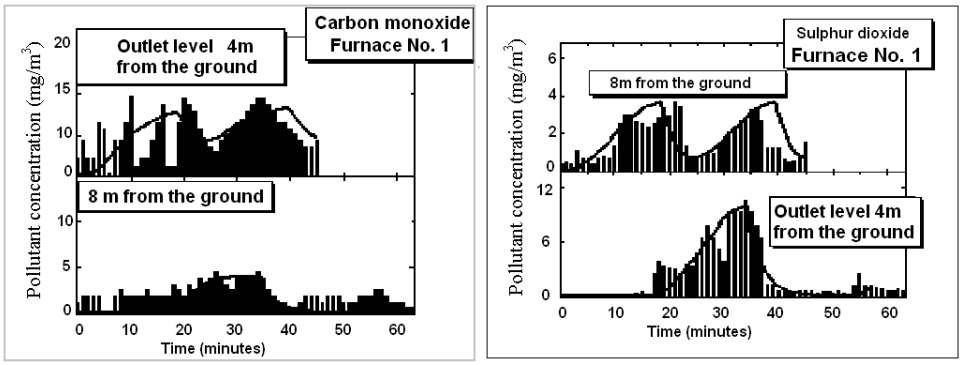

Fig. 11 – Measured (histograms) and computed (continuous curves) time-variation of the pollutant concentration in two compartments of the unit: a) sulfur dioxide; b) carbon monoxide.

Figure 12 shows a sample result of a model computation (continuous lines), which correlates very well with measured concentrations (histograms) of SO_2 near one of the furnaces of a real unit.

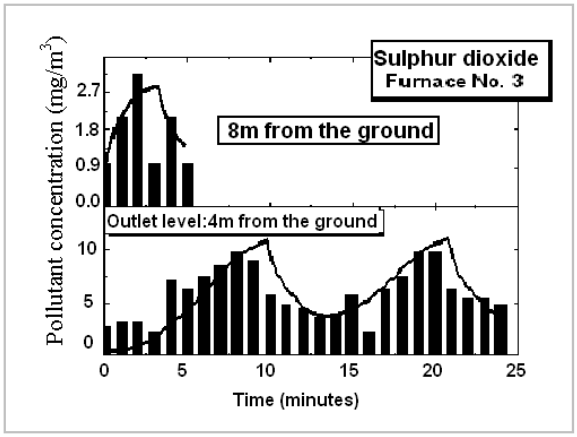

Fig. 12 – Measured (histograms) and computed (continuous curves) time-variation of the pollutant concentration in the C3 furnace of the unit for sulfur dioxide shows a sample result of a model computation (continuous lines), which correlates very well with measured concentrations (histograms) of SO_2 near one of the furnace of a real unit.

5. CONCLUSIONS

The INPOLL model is best suited for a metallurgical unit with several furnaces enclosed in a partitioned hall with a ventilation system.

It describes the evolution of concentrations of chemically inert gaseous pollutants in the working space, in various operational alternatives.

The operation schemes for the furnaces can be varied to reproduce complex situations when they are discharged in succession or simultaneously.

Due to its flexible construction, the approach can be applied to all types of indoor pollution for industrial or non-industrial areas.

The model can be used to evaluate various filtration and ventilation systems.

The obtained results demonstrate that the model is more accurate in calculating the optimal operation regimes by varying functional parameters (like ventilation fluxes or the time gap between furnace discharges).

The described computational model can be used to optimize the operation of a multiple-furnace metallurgical unit in terms of the productivity, the overall concentrations of related gaseous pollutants and energy consumption.

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