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THE GAUSSIAN AIR POLLUTION DISPERSION MODEL WITH VARIABILITY OF THE INPUT PARAMETERS TAKEN INTO ACCOUNT. II. VERIFICATION OF THE MODEL

The performance of the SPM model for simulation of the transport and dispersion of air pollutants emitted from a group of point sources, formulated in Part I, is evaluated. The model verification is carried out using the data set obtained during the measurement experiment with a tracer SF_6 which was conducted in Kincaid, Illinois, U.S.A. Different statistical measures were applied. Statistical analysis carried out for the developed model provided encouraging results. They are much better than the results obtained for the Pasquill model which is used in the routine calculations in Poland.

1. INTRODUCTION

Part I of this study [6] describes the formulation of the segmented Gaussian plume model (SPM) for simulation of the transport and dispersion of the air pollutants emitted from a group of point sources. The developed model allows us to take into account the change of the emission parameters and meteorological conditions as well as the variability of the terrain conditions and is based on the meteorological data recorded during the routine measurements carried out in Poland.

This part is devoted to the empirical verification of the SPM model. It is carried out in order to assess the performance of the developed model. The statistical analysis of two concentration sets – calculated and measured – enables the model verification. In addition, the comparison between the performance of the SPM model and the performance of the Pasquill model, which in used in the routine calculations in Poland, is carried out.

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Section 2 presents the requirements for the data set for the verification of the developed model and the analysis of the possibilities of obtaining such a data set. Section 3 describes the data set from the measurement experiment in Kincaid, Illinois, U.S.A., which was used for the model verification. The results of the statistical evaluation of the SPM model and the comparison between the performance of SPM model and that of the Pasquill model used in the routine calculations in Poland are discussed in Section 4.

2. REQUIREMENTS FOR THE DATA SET FOR THE SPM MODEL EVALUATION AND ANALYSIS OF THE POSSIBILITIES OF OBTAINING SUCH A DATA SET

In order to verify the developed SPM, the data set which meets the following requirements is needed:

1. The measured concentration of the pollutant should be averaged over the time interval equal to the model discrete step. The value of the time interval ranges from 30 minutes to 1 hour.
2. The pollutant should be easily identified in order to avoid the influence of the background concentration. The SF_6 tracer meets this condition.
3. The space scale of the measurements should be large enough to allow the time of the transport of the pollutant from the stack to the receptor to be longer than the model discrete step. The change in meteorological conditions on the way of the transport of the pollutant from the stack to the receptor should take place.
4. The change in time of the emission parameters is required.
5. The measurements should be carried out at the plain terrain.

It was not possible to perform the experiment which would meet the specified conditions within the scope of the described study. The possibilities of obtaining the data set for model verification were analyzed.

In Poland, monitoring of the air pollution covering the simultaneous measurements of emission and imission of the pollutants as well as the meteorological parameters is carried out seldom and none of the experiments met the requirements specified above.

The review of the measurement experiments described in the paper *Directory of atmospheric tracer experiments* [1] indicates that no experiments carried out in Europe in flat terrain can be used due to the space distance.

The model verification was based on the data collected during the experiment carried out in Kincaid, Illinois, U.S.A. The measurement programme of this experiment was realized in such a way that it was possible to find the measurement series which met all the requirements [5], [7].

3. THE MEASUREMENT EXPERIMENT AT KINCAID AND SELECTION OF MEASUREMENT SERIES

The measurements with a use of the tracer in Kincaid were carried out during the three measurement periods: 22.04–10.05.1980, 9.07–29.07.19080, 9.05–1.07.1981.

The hexafluoride sulfide (SF_6) was emitted from the stack of the Kincaid Generation Station. The stack height was 187 m and its diameter was 9 m. The release rate of SF_6 was between 45 and 90 kg. The stack emission parameters were measured continuously and the results were averaged over 1 hour.

A network of approximately 1500 tracer sampling locations was used at the Kincaid site. The network design consisted of concentric circles at average radial distance of 0.5, 1, 2, 3, 5, 7, 10, 15, 20, 30, and 50 km from the power plant. Using the existing roadway network, the downwind distance of the samples assigned to an arc varied as much as 20 percent of the mean distance. The monitors on the arcs were spaced at azimuthal intervals ranging from 2 to 8 degrees.

The SF_6 concentrations were measured continuously and averaged over 1 hour. Each day the measurement period lasted from 6 to 9 hours. The total time of measurements was 300 hours. About 200 samplers were in operation each hour in a series from 5 to 7 arcs downwind from the source. The width of this instrumented sector ranged from 10 to 190 degrees, depending on atmospheric stability.

Two meteorological towers, 100 and 10 m high, were used to measure the temperature, wind velocity, its direction and turbulence. The towers were located approximately 1 km from the stack. The meteorological parameters were measured at the heights: 10, 30, 50, and 100 m. The continuous data were averaged over 1 hour. The continuous solar and terrestrial radiation data were collected at the ground near to the base of the tower. Each hour atmospheric pressure and precipitation were measured and the cloud cover was specified. In addition, the vertical sounding of the temperature, wind velocity and its direction was carried out.

The author has obtained the measurement data which cover the period from 12 to 31 of May, 1981. Five episodes, which met the requirements, were selected for the model verification:

12.05.1981, 12–13 a.m.,
16.05.1981, 9–10 a.m.,
16.05.1981, 12–13 a.m.,
24.05.1981, 17–18 p.m.,
27.05.1981, 10–11 a.m.

The selected episodes are given the names based on the day and the hour of the measurements. According to this rule, for example, the last measurement episode is given a symbol: D27H11 (27-th day, at 11-th ST time).

The values of the meteorological and emission parameters for the selected periods are shown in table 1.

Table 1

Meteorological and emission parameters for the selected periods

Measurement period	Earlier episode	Meteorological parameters: Atmospheric stability	Meteorological parameters: Mixing layer depth	Wind velocity and direction at $z = 100$ m		Temperature and atmospheric pressure at $z = 186$ m		Stack emission parameters: SF_6 emission	Velocity and temperature of stack gases	
			(m)	(m/s)	(degrees)	(°C)	(hPa)	(kg/h)	(m/s)	(K)
	D24H16	3	2000	5.5	267.1	21.0	966.0	61.69	14.8	395.0
	D24H17	3	2000	4.6	267.3	19.8	966.0	63.05	14.9	396.6
D24H18		4	1002	5.2	268.1	19.9	965.7	65.77	15.4	395.8
	D27H10	2	675	2.3	6.3	19.4	967.0	45.81	15.7	440.0
D27H11		1	2000	1.6	19.3	21.1	968.0	41.73	15.5	442.0
	D16H8	2	2000	5.9	142.7	16.2	973.2	58.06	14.17	442.0
	D16H9	2	2000	5.0	128.1	16.8	973.2	58.51	16.00	442.0
D16H10		3	2000	6.2	110.9	18.2	973.4	58.97	17.92	417.0
	D12H10	1	644	1.7	147.7	11.8	976.0	41.28	13.00	408.9
	D12H11	1	614	2.4	154.4	11.8	975.9	54.43	13.10	407.4
D12H13		1	742	3.3	123.1	13.1	975.1	31.75	13.90	403.8
	D16H11	3	2000	6.8	117.4	18.9	973.7	60.33	13.00	409.9
	D16H12	3	2000	6.5	113.6	20.7	973.5	58.97	13.10	407.7
D16H13		3	2000	7.7	129.1	20.0	974.4	58.51	13.90	403.8

The selected measurement periods differ in meteorological conditions and stack emission parameters. During the period D24H18, the changes of atmospheric stability and the depth of mixing layer were noted. During the period D27H11, the change of the wind direction was observed in addition. In the case of episode D27H11, the change of atmospheric stability and wind direction occurred. The period D12H13 was characterized by the essential difference in the emission intensity of the pollutants, the change of the mixing layer depth and the wind direction. In the case of the D16H13 episode, there was the change of the wind direction. In all considered cases, wind changed its velocity.

In the calculations, the constant roughness coefficient was taken due to the small variability of the terrain. Its value ZO equals 0.21 m.

In the model verification, only the measurement points located on the arcs whose radii were greater than the distance of the 1 hour transport of the pollutant from the stack were considered.

4. RESULTS OF THE SPM MODEL VERIFICATION

In the SPM model verification, the statistical measures which are most often used in statistical analysis and which have relatively simple explanation were applied. They are as follows: mean of the measured concentration ($\bar{C}_m$), mean of the calculated concentration ($\bar{C}_c$), mean of the absolute deviation ($\bar{d}$), root mean square error ($\bar{e}$), coefficient of variation (W), correlation coefficient (R), regression line with the coefficients: slope (a) and intercept (b). These statistical measures are given by the following formulae [2]–[4]:

$$\bar{C}_m = \frac{1}{N} \sum_{i=1}^{N} C_{mi}, \tag{1}$$

$$\bar{C}_c = \frac{1}{N} \sum_{i=1}^{N} C_{ci} \tag{2}$$

where N is the number of data points, C_{mi}, C_{ci} are the measured and calculated concentrations at the i-th point, respectively.

$$\bar{d} = \frac{1}{N} \sum_{i=1}^{N} |C_{mi} - C_{ci}|, \tag{3}$$

$$\bar{e} = \left[\frac{1}{N} \sum_{i=1}^{N} (C_{mi} - C_{ci})^2\right]^{0.5}, \tag{4}$$

$$W = \frac{\left[\frac{1}{N-1} \sum_{i=1}^{N} (C_{mi} - C_{ci})^2\right]^{0.5}}{\frac{1}{N} \sum_{i=1}^{N} C_{mi}}, \tag{5}$$

$$R = \frac{\sum_{i=1}^{N}(C_{mi} - \bar{C}_m)(C_{ci} - \bar{C}_c)}{\left[\sum_{i=1}^{N}(C_{mi} - \bar{C}_m)^2 \sum_{i=1}^{N}(C_{ci} - \bar{C}_c)^2\right]^{0.5}}, \tag{6}$$

$$\hat{C}_c = a + bC_m \tag{7}$$

where a, b are calculated by means of the least square method.

Statistical measures were also calculated for the Pasquill model used in the routine calculations in Poland which allowed the comparison of the performances of these two models.

The statistical measures for the SPM model and Pasquill model are given in table 2. The means of the concentrations calculated according to the SPM model for the two cases, from the five considered in the verification, show a very good agreement with the measurements (D24H18 and D16H13). For the series D27H11 and D12H14 there is also observed a good agreement. In general, the concentrations calculated according to the SPM model and the concentrations measured are in a solid agreement. For the concentrations calculated on the basis of the Pasquill model, this agreement is much worse.

The value of the proportion of the mean of the absolute deviation to the mean of the measured concentration should be smallest. It is considered that for a good model this proportion should be less than unity. The values of this proportion range from 0.373 to 0.712 and from 0.636 to 1.067 for the developed model and for the Pasquill model, respectively.

The correlation coefficients in the case of the SPM model have all values much higher than the critical values of this parameter at the confidence level of 5%. In the Pasquill model, for three cases from five considered the correlation coefficients do not reach the critical values (D16H10, D12H13, D16H13).

The values of the coefficient of variation of the developed model vary from 0.702 to 1.986. For the Pasquill model, the values of this measure range within 1.225–2.885. It is considered that the values of the coefficient of variation for the good model should be less than unity. The great values of this coefficient are due to the great values of the root mean square error.

The great values of the root mean square errors can be explained by the analysis of the physical nature of the pollutant transport and dispersion for distances.

The trajectory of the wind is influenced by the turbulence movements of different scale. As a result, the real axis of the plume oscillates around the trajectory, which in the SPM model is approximated by the chain of segments. The verification of the models of air pollutant dispersion described in *Diagnostic validation of plume models at a plain site* [5] carried out using the Kincaid data (i.e. the same data which were used to verify the SPM model) shows that for most of the considered models, including these used in the U.S.A. for the routine calculations, the statistical

Table 2

Statistical measures for the SPM and the Pasquill models

Statistical measure	Units	Measurement period									
		D24H18		D27H11		D16H10		D12H13		D16H13	
		Model									
		SPM	PASQ	SPM	PASQ	SPM	PASQ	SPM	PASQ	SPM	PASQ
Number of measurement points	–	75		23		34		40		37	
Radius of measurement arc	km	30; 50		10; 15		50		15; 20		50	
Mean of the measured concentration	ppt	7.516		46.691		8.132		58.005		2.655	
Mean of the calculated concentration	ppt	7.541	9.661	34.457	18.576	2.609	0.788	33.773	2.174	2.486	1.415
Mean of the absolute deviation	ppt	4.137	5.860	17.397	29.677	5.740	8.093	38.996	55.831	1.896	2.846
Proportion of mean of the absolute deviation to mean of the measured concentration	–	0.550	0.780	0.373	0.636	0.706	0.995	0.672	0.963	0.712	1.068
Root mean square error	ppt	14.227	20.584	32.037	55.928	12.706	15.891	60.927	90.892	5.196	7.585
Coefficient of variation	–	1.906	2.757	0.702	1.225	1.586	1.983	1.064	1.587	1.977	2.885
Correlation coefficient	–	0.861	0.849	0.957	0.983	0.652	0.216	0.643	0.384	0.732	0.274
Regression coefficient – slope	ppt	−0.449	−0.459	3.582	2.140	0.387	0.459	11.617	1.245	0.944	1.063
Regression coefficient – intercept	–	1.063	1.346	0.661	0.352	0.273	0.040	0.382	0.016	0.579	0.132

measures do not reach satisfactory values. In practice, the group of emission sources is considered. In that case, much better results can be obtained.

Ideal values of the regression coefficients, i.e. the model results and the measurements are in a full agreement, can be specified as zero for the slope of the regression line and unity for the intercept. For the SPM model, the values of the slope for four cases from the five considered episodes are less than 10% of the mean measured concentration. The intercepts for the three cases are greater than 0.5. For the rest of the cases, they vary from 0.273 to 0.383. For the Pasquill model the results are worse.

In general, the results of the statistical analysis for the SPM model are encouraging and much better than these obtained for the Pasquill model.

5. CONCLUSIONS

In two parts of the paper, the segmented Gaussian plume model has been formulated and its verification carried out with the use of the data set from the measurement experiment at Kincaid site, Illinois, U.S.A., has been discussed. Based in this study the following conclusions can be formulated:

1. The developed segmented plume model of air pollutant transport and dispersion (SPM) allows us to simulate pollution which consists in pollutant emission from a group of poit sources. In such a process, the change in time of stack emission parameters and meteorological conditions as well as the spatial variability of topographical conditions are taken into account. The model being based on the meteorological data from the routine measurements carried out in Poland enables us to maintain the simplicity of the Gaussian type model.

2. The SPM model verification carried out using the data set from the measurement experiment performed at Kincaid, Illinois, U.S.A., confirms the usefulness of the model in calculating the distributions of the air pollutant concentrations under nonhomogeneous and nonstationary conditions specified above.

3. The comparison of the statistical measures, used in the model evaluation, calculated for the SPM and Pasquill models shows that for all the cases considered (five episodes from the Kincaid experiment) the SPM model gives much better results.

4. The SPM model can be used to calculate the distributions of the pollutant concentrations averaged over 30-minutes, 24-hours and one year as well as the frequencies of the cases when the accepted levels of concentrations are exceeded. However, the SPM model allows us to extend the space scale of the calculations to few tens of km, while the Pasquill model should not be used for the distances greater than 10 km.

5. The space distance of the calculations of the SPM model makes it possible to use this model to simulate the flow of the pollutants to the specific region.

6. The fact that the SPM model takes into account the change of the emission parameters in time allows us to apply this model to the air quality assessment when accidental releases take place.

7. It is possible to extend the range of the SPM model applications to the simulation of the transport and dispersion of the air pollutant emitted from the line and area sources.

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GAUSSOWSKI MODEL ROZPRZESTRZENIANIA SIĘ ZANIECZYSZCZEŃ W ATMOSFERZE UWZGLĘDNIAJĄCY ZMIENNOŚĆ PARAMETRÓW WEJŚCIOWYCH CZĘŚĆ II. WERYFIKACJA MODELU

Przedstawiono wyniki weryfikacji segmentowego gaussowskiego modelu smugi (SPM) dla symulacji transportu i dyspersji zanieczyszczeń powietrza emitowanych z grupy emitorów punktowych. Model zweryfikowano korzystając z danych, otrzymanych podczas wykonywania eksperymentu w Kincaid, Illinois, USA. Statystyczne wskaźniki oceny modelu obliczono również dla modelu Pasquilla, który w Polsce jest używany do obliczeń rutynowych. Umożliwiło to porównanie obu modeli.

МОДЕЛЬ ГАУССА РАСПРОСТРАНЕНИЯ ЗАГРЯЗНЕНИЙ В АТМОСФЕРЕ, УЧИТЫВАЮЩАЯ ИЗМЕНЧИВОСТЬ ВХОДНЫХ ПАРАМЕТРОВ. ЧАСТЬ II. ПРОВЕРКА МОДЕЛИ

Представлены результаты проверки сегментной модели полосы Гаусса (SPM) для имитации транспорта и дисперсии загрязнений воздуха, эмиттируемых из комплекса точечных эмиттеров. Модель была проверена с использованием данных, полученных во время выполнения эксперимента в Кинкед, Иллинои, США. Статистические показатели оценки модели были рассчитаны для модели Паскаля, которую в Польше применяют для рутиновых расчетов. Это способствовало сравнению обеих моделей.