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EMISSION OF POLLUTANTS INTO THE AIR DURING EXPLORATION OF COALBED METHANE**

1. INTRODUCTION

In recent years increased attention has been pay to air pollution in Poland. More and more often we hear new information about the disastrous state of air quality in the vicinity of large urban agglomerations. Based on WHO data from 2013, 33 of the 50 most polluted cities by PM2.5 in Europe are in Poland [11]. The most dangerous pollutants reaching ambient air include mainly dust PM10, PM2.5 and benzo(a)pyrene, which is a strongly carcinogenic compound. In Poland, poor condition of the air is influenced by industry, transport and pollution produced during the combustion of poor quality coal in households. Most of the previously mentioned cities in Poland, with poor air quality are located in the Upper Silesian Coal Basin area [10]. The lack of alternative energy sources means that the main source of energy in this region is coal.

A source of clean energy could be a methane adsorbed in coal. In Poland, the economic use of methane from coal seams has been recognized as one of the priority objectives of energy policy. According to documentation in the Upper Silesian Coal Basin, documented methane resources in coal seams are 89.1 billion m^3 [4].

Recently, after the failures of foreign investors such as Texaco or Amoco in the 1990s, a new attempts were made to obtain methane from coal seams [2]. New research operations were carried out using drilled wells Wesoła PIG-1 and Wesoła PIG-2H and Gilowice-1 and Gilowice-2H [3]. The first project did not bring the expected results, while the Gilowice project allowed methane production at a level of 5000 m^3 a day [8].

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The consortium PGNiG and PIG-PIB is planning to continue research, related to the extraction of methane from coal seams. Methane from coal seams is extracted using a pair of wells – a vertical one which is used to extract methane and reservoir water, and a horizontal one which is used as a drainage well [2]. In order to increase the production of methane, hydraulic fracturing should be carried out. Drilling and hydraulic fracturing operations are carried out with drilling equipment and high-pressure pumps, which are powered by combustion engines of very high power. One negative result of this work is the emission of pollutants in to the air.

2. METHODOLOGY FOR AIR POLLUTION MODELING

Emission of pollutants to the air is determined on the basis of the reference methodology for modeling levels of substances in the air, described in the Regulation of the Minister of the Environment regarding reference values for certain substances in the air (Journal of Laws No. 16 item 87 of January 26, 2010). The concentration of the gaseous substance for one hour at the point *Xp*, *Yp*, *Zp* is calculated using formula (1) [6]:

$$S_{xyz} = \frac{E_g}{2 \cdot \pi \cdot u \cdot \sigma_y \cdot \sigma_z} \exp \cdot \left(-\frac{y^2}{2 \cdot \sigma_y^2} \right) \left\{ \exp \cdot \left[-\frac{(z-H)^2}{2 \cdot \sigma_z^2} + \exp \cdot \left[-\frac{(z+H)^2}{2 \cdot \sigma_z^2} \right] \right] \right\} \cdot 1000 \quad (1)$$

where:

- S_{xyz} – concentration of (gaseous) contamination at point (x, y, z) during 1 hour period [μg/m^3],
- E_g – contamination emission [mg/s],
- H – effective height of emitor [m],
- u – average wind velocity in an air layer from $z = h$ to $z = H$ [m],
- y – the component of the emitter's distance from the point for which the calculation is made, perpendicular to the direction of the wind [m],
- z – height for which the concentration of the substance in the air is calculated [m],
- σ_y – horizontal diffusion coefficient [m],
- σ_z – vertical diffusion coefficient [m].

On the basis of the obtained results, the range of calculation of the substance levels in the air is checked, which includes the shortened range and the full range. If the preliminary calculation shows that the conditions defined in the formula (2) are fulfilled, then calculation are finished [6]:

$$S_{mm} \le 0.1 \cdot D_1 \quad \text{or} \quad \sum_e S_{mm} \le 0.1 \cdot D_1 \quad (2)$$

If the conditions of the shortened range are not meet the requirements, the distribution of the maximum concentrations of substances in the air for one hour, including the statistics of meteorological conditions, should be calculated over the entire area to check whether at each point on the land surface has been meet condition defined by formula (3) [6]:

$$S_{mm} \leq D_1 \tag{3}$$

If the calculations shows that the condition described in the formula 4 is fulfilled for the emitters, then the calculation should be finished [6]:

$$S_{mm} \leq 0.1 \cdot D_1 \tag{4}$$

For a group of emitters which condition (4) is not fulfilled or for a single emitter for which the condition specified in the shortened range is not meet, should be calculated the distribution of air concentrations and checked whether at each point of the surface has been meet for the average annual concentrations specified by formula (5) [6]:

$$S_a \leq D_a - R \tag{5}$$

Acceptable levels of substances in the air are considered to be meet, if the frequency of exceeding D_1 by averaged over one hour is not more than 0.274% of the time of the year for sulphur dioxide and 0.2% of time per year for other substances [6]. In case the concentration caused by substance emission from all emitters exceeds a reference value or the permissible level of a substance in the air and the frequency of exceeding the $P(D_1)$ is calculated. Acceptable frequency of exceeding of D_1 is maintained, if the calculated 99.8% percentile of one hour concentrations ($S_{99.8\%}$) is lower than the reference value or the permissible level of substances in the air. This means that for substances whose concentrations do not meet the criteria (4), should be verified by following criteria to set out in formulas (6), (7) and (8) [6]:

$$S_{mm} \leq D_1 \tag{6}$$

$$S_{99.8\%} \leq D_1 \tag{7}$$

$$S_a \leq D_a - R \tag{8}$$

Due to the legal regulations in Poland, emission of pollutants from devices used for extraction of coal bed methane should meet standards regarding concentrations of pollutants into the air. The reference values of the concentrations of substances emitted should not exceed the values specified in the polish law. The admissible values for the analyzed substances in air have been presented in Table 1 [6, 7].

Table 1

Admissible value for substances in air [6, 7]

Pollutant	Admissible value		
	Max 1-hour concentrations	Average yearly concentrations	Incidence of exceeding admissible values
	D_1	D_a	$P(D_1)$
	[µg/m^3]	[µg/m^3]	[%]
NO_2	200	40	0.2
SO_2	350	20	0.274
PM10	280	40	0.2
CO	30 000	0	0.2

3. CALCULATION OF POLLUTION EMISSION INTO THE AIR

The first advanced works related to the methane extraction from the coal seams in Poland were carried out in 2013–2015 [3]. The project was run by Polish Geological Institute together with Katowicki Holding Weglowy and consisted demethanization of coal seams. For this purpose, two wells were drilled for methane extraction from the coal seams. Wesoła PIG-1 well was drill as vertical one with a depth of 1000 m MD, whereas Wesoła PIG-2H was drilled as an open hole with horizontal section (1918 m MD/904 m TVD) [3]. Drilling time was 30 days and 45 days respectively [3]. In addition, eight hydraulic fracturing stage were carried out in the horizontal section. Another project was carried out in 2016–2017 by Polish Oil and Gas Company and Polish Geological Institute. Work involved, reconstruction of the Gilowice-2H well drilled in 2012, by Dart Energy and six-stage hydraulic fracturing operations. The drilling works for Gilowice-1 well (1088 m MD/1044.5 m TVD) took 17 days, while Gilowice-2H (2300 m MD/856 m TVD) was carried out for 28 days [2, 3]. Duration of hydraulic fracturing operation was 3 hours for each stage. For drilling operations of the Gilowice-1 and Gilowice-2H, a Skytop Brewster TR-800 device was used. The drilling device was powered by two CAT 3408 engines – 500 HP each, whereas the mud pumps were powered by 750 HP CAT D398 engine [1]. For hydraulic fracturing operations were used 6 high-pressure pumps driven by Stewart & Stevenson FT-2251T engine – 2250 HP and one blender driven by Stewart & Stevenson MT-132HP engine – 1450 HP [9]. Parameters of all emitters are presented in Table 2.

Table 2

Characteristic of emitters [1, 9]

Parameter	Drilling operations		Hydraulic fracturing	
	CAT 3408	PZ-8	FT-2251T	MT-132HP
Amount of emitters [pcs]	2	1	6	1
Horsepower rating [kW]	367	552	1 655	1 066
Height of emitter [m]	4.0	3.0	4.0	4.0
Diameter of emitter [m]	0.3	0.3	0.4	0.4
Efficiency [%]	75	75	90	90

For calculations emissions of particulate matter (PM10), sulphur dioxide (SO_2), nitrogen oxides (NO_X) and carbon monoxide (CO), emission index presented in the "Large Stationary Diesel and All Stationary Dual-fuel Engines, Volume I, Chapter 3: Stationary Internal Combustion Sources" were used. The emission factors used in calculations are presented in Table 3.

Table 3

Emission factors for stationary diesel engines over 560 kW fed with diesel oil [10]

Pollutant	Emission index referred to engine power (output) [g/kWh]
Nitrogen oxides (NO_X)	7.904
Sulphur dioxide (SO_2),	$4.918 \cdot S$
Particulate matter (PM10)	0.4261
Carbon monoxide (CO)	3.344
S – sulphur content in fuel 0.01%	

Results of hourly and annual emission of pollutants emitted to air from generators during drilling and hydraulic fracturing operations are presented in Table 4.

Specialized OPA03 software was used for modeling of pollutants spread in ambient air during extracting of methane from coal seams. Modeling of the spread of pollutants was carried out in the area where previous research works were carried out – Upper Silesian Coal Basin. Important parameter required to calculate the spread of pollutants in the air is the background of pollution in interest area. For the considered area based on the WIOŚ data, the following background conditions of air pollution were adopted [12]:

- particular matter PM10 – 25 μg/m^3,
- sulphur dioxide SO_2 – 8 μg/m^3,
- nitrogen oxides NO_2 – 20 μg/m^3.

For other substances, the background level was set at 10% of the permissible concentration in the air.

Table 4

Hourly and annual emission of pollutants emitted to air from generators

Pollutant	Vertical drilling		Horizontal drilling		Hydraulic fracturing	
	Emission of pollutants					
	[kg/h]	[Mg/a]	[kg/h]	[Mg/a]	[kg/h]	[Mg/a]
NO_2	10.16	4.15	10.16	6.83	60.75	1.56
SO_2	0.00006	0.00003	0,00006	0.00004	0.00038	0.00001
PM10	0.55	0.22	0.55	0.37	3.28	0.085
CO	4.30	1.75	4,30	2.89	25.70	0.61
Vertical drilling: 408 h, Fuel consumption: 0.047 m^3/h (drilling unit), 0.079 m^3/h (mud pump) Horizontal drilling: 672 h, Fuel consumption: 0.047 m^3/h (drilling unit), 0.079 m^3/h (mud pump) Hydraulic fracturing: 18 h, Fuel consumption: 0.19 m^3/h (high pressure pump), 0.12 m^3/h (blender)						

3.1. Drilling works

Calculated results of the spread of pollutants in the air during drilling work shows that the maximum hourly concentration of nitrogen oxides was 2661.8 μg/m^3, sulphur oxides 0.018 μg/m^3, particular matter 73.4 μg/m^3, and for carbon monoxide 1129.2 μg/m^3. The maximum annual concentrations for nitrogen oxides was 19.33 μg/m^3, sulphur oxides 0.00013 μg/m^3, particular matter 0.53 μg/m^3 and carbon monoxide 8.19 μg/m^3. The annual frequency of exceeding of nitrogen oxides was 2.23%. The calculated 99.8% percentile of nitrogen oxides was 1673.1 μg/m^3, for particular matter 46.1 μg/m^3, and for carbon monoxide 709.7 μg/m^3. All results of modeling the spread of pollutants in the air during drilling operations are presented in Table 5.

Analyzed data in Table 6 shows that for nitrogen oxides and particulate matter it is necessary to determine permissible emissions in the full range. For these substances, the condition specified in the shortened range of calculations of the levels of substances in the air $\Sigma S_{mm} = 0.1D_1$ was not met. In Table 6 the results of calculations in the shortened range.

Table 5

Calculation of pollutant concentrations during drilling operations

Pollutant	Emission		Frequency of exceeding $P(D_1)$	$S_{99.8\%}$ percentile
	Maximum 1 h concentration S_{mm}	Maximum yearly concentration S_a		
	[μg/m^3]	[μg/m^3]	[%]	[μg/m^3]
NO_2	2 661.8	19.33	2.23	1 673.1
SO_2	0.018	0.00013	0.0	0.01
PM10	73.4	0.53	0.0	46.1
CO	1 129.2	8.19	0.0	709.7

Table 6

Calculation of pollutant concentrations in the shortened range

Pollutant	Emission drilling operations S_{mm}	Admissible value D_1	Evaluation
	[μg/m^3]	[μg/m^3]	
NO_2	2 661.8	200	$0.1D_1 < S_{mm} < D_1$
SO_2	0.018	350	$0.1D_1 < S_{mm} < D_1$
PM10	73.4	280	$0.1D_1 < S_{mm} < D_1$
CO	1 129.2	30 000	$S_{mm} < 0.1D_1$

Figures 1 and 2 show graphical results of modeling the spread of pollutants in the air during drilling operations for vertical and horizontal well in relation to the maximum hourly concentrations.

Table 7 presents results of the maximum annual emission calculation during drilling operations as well as average yearly concentration reduced by the background. PM10 and NO_2 are considered to meet the conditions set out in the full range of air substance levels.

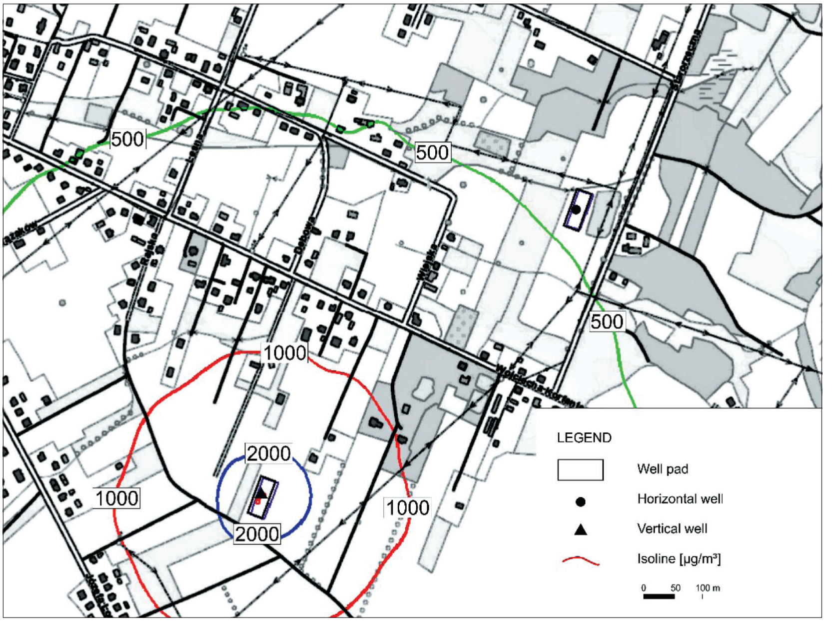

Fig. 1. Spatial distribution of NO_2 – maximum 1 hour NO_x concentration during vertical drilling

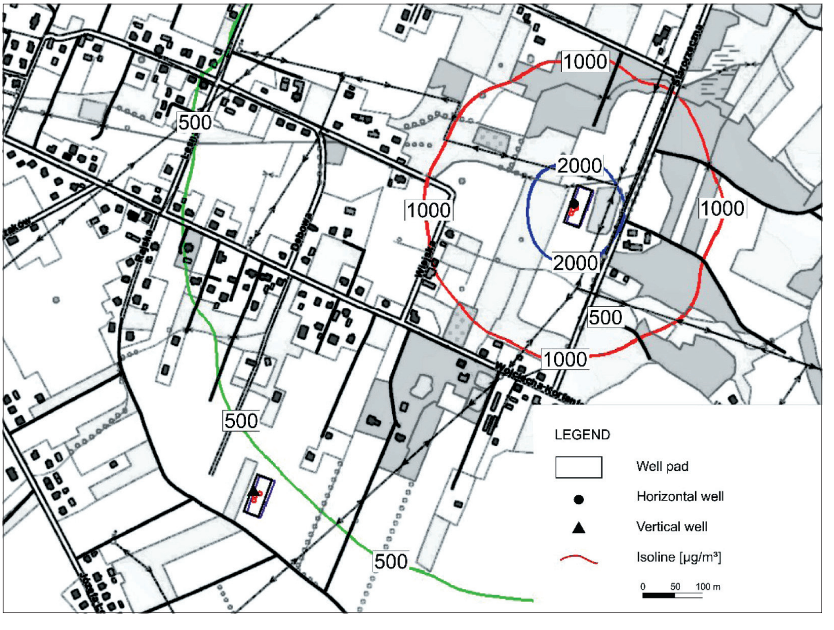

Fig. 2. Spatial distribution of NO_2 – maximum 1 hour NO_x concentration during horizontal drilling

Table 7

Calculation of pollutant concentrations in the full range

Pollutant	Calculated emission S_a	Average yearly concentrations reduced by the background value $[D_a - R]$	Evaluation
	[μg/m^3]	[μg/m^3]	
NO_2	19.33	20	$S_a < D_a - R$
PM10	0.53	15	$S_a < D_a - R$

Figure 3 presents graphical results of modeling the spread of pollutants in the air during drilling operations vertical and horizontal wells in relation to the maximum annual concentrations.

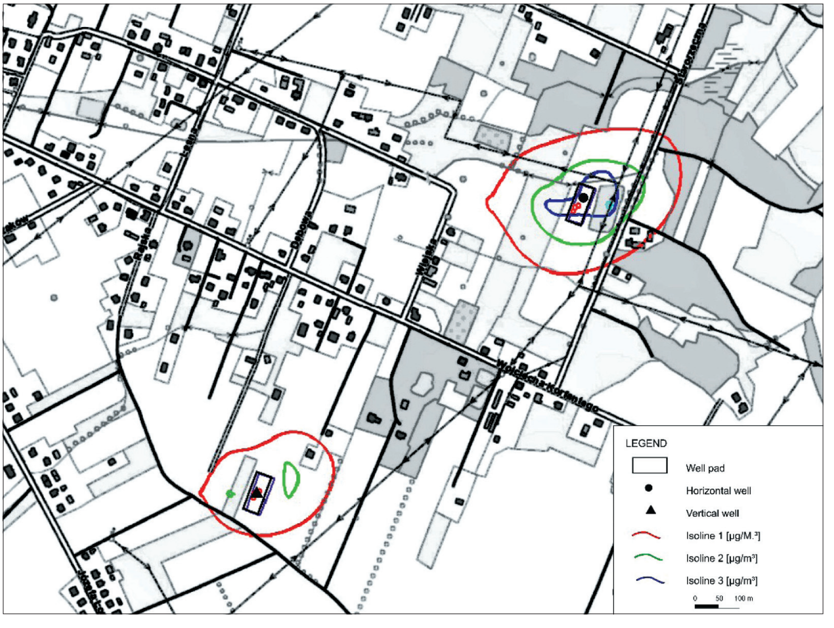

Fig. 3. Spatial distribution of NO_2 – maximum yearly NO_x concentration during drilling operations

The analysis of the results of calculations of the annual frequency of exceedances of substances in the air shows that this condition was not met in relation to nitrogen oxides. Table 8 presents the results of the annual frequency of exceeding for nitrogen oxides for the drilling phase.

Table 8

Calculation of frequency of exceeding

Pollutant	Frequency of exceeding $P(D_1)$	Admissible value D_1	Evaluation
	[%]	[%]	
NO_2	2.23	0.2	$P(D_1) < 0.2$

Subsequent calculations were carried out to $S_{99.8\%}$ percentile concentration of 1 hour. $S_{99.8\%}$ percentile was 212.43 g/m^3 and was higher than the allowable concentration. Table 9 shows the results of the $S_{99.8\%}$ percentile calculation.

Table 9

Calculation of $S_{99.8\%}$ percentile

Pollutant	$S_{99.8\%}$ percentile	Admissible value D_1	Evaluation
	[µg/m^3]	[µg/m^3]	
NO_2	1 673.1	200	$S_{99.8\%} \leq D_1$

3.2. Hydraulic fracturing

Calculations of the spread of pollutants in air during hydraulic fracturing operations of coal seams in Upper Silesia Coal Basin show that the maximum hourly concentration of nitrogen oxides was 15 312.8 µg/m^3, sulphur oxides 0.093 µg/m^3, PM10 414.96 µg/m^3, and for carbon dioxide 6473.28 µg/m^3. The maximum annual concentrations for NO_2 was 3.45 µg/m^3, SO_2 – $2 \cdot 10^{-5}$ µg/m^3, PM10 – 0.094 µg/m^3 and CO – 1.47 µg/m^3. The annual frequency of exceeding for nitrogen oxides was 0.074% and for PM10 – 0.007%, for the other analyzed substances there was no exceedance of the annual frequency of exceeding. The calculated $S_{99.8\%}$ percentile for all substances was 0.0 µg/m^3. All the results of modeling the spread of pollutants in the air during hydraulic fracturing operations are presented in Table 10.

Analyzed data in Table 11 shows that for nitrogen oxides, particulate matter and carbon dioxide, it was necessary to determine permissible emissions in the full range. For these substances, the condition specified in the shortened range of calculations of the levels of substances in the air $\Sigma S_{mm} = 0.1D_1$ was not met.

In Figure 4 graphical results of modeling the spread of pollutants in the air during hydraulic fracturing in relation to the maximum hourly concentrations are presented.

Table 10

Calculation of pollutant concentrations in the shortened range

Pollutant	Emission		Frequency of exceeding $P(D_1)$	$S_{99.8\%}$ percentile
	Maximum 1 h concentration S_{mm}	Maximum yearly concentration S_a		
	[μg/m^3]	[μg/m^3]	[%]	[μg/m^3]
NO_2	15 312.8	3.45	0.074	0.0
SO_2	0.093	$2 \cdot 10^{-5}$	0.0	0.0
PM10	414.96	0.094	0.007	0.0
CO	6 473.28	1.47	0.0	0.0

Table 11

Calculation of pollutant concentrations in the shortened range

Pollutant	Calculated emission S_{mm}	Admissible value D_1	Evaluation
	[μg/m^3]	[μg/m^3]	
NO_2	15 312.8	200	$0.1D_1 < S_{mm} < D_1$
SO_2	0.093	350	$0.1D_1 < S_{mm} < D_1$
PM10	414.96	280	$0.1D_1 < S_{mm} < D_1$
CO	6 473.28	30 000	$S_{mm} < 0.1D_1$

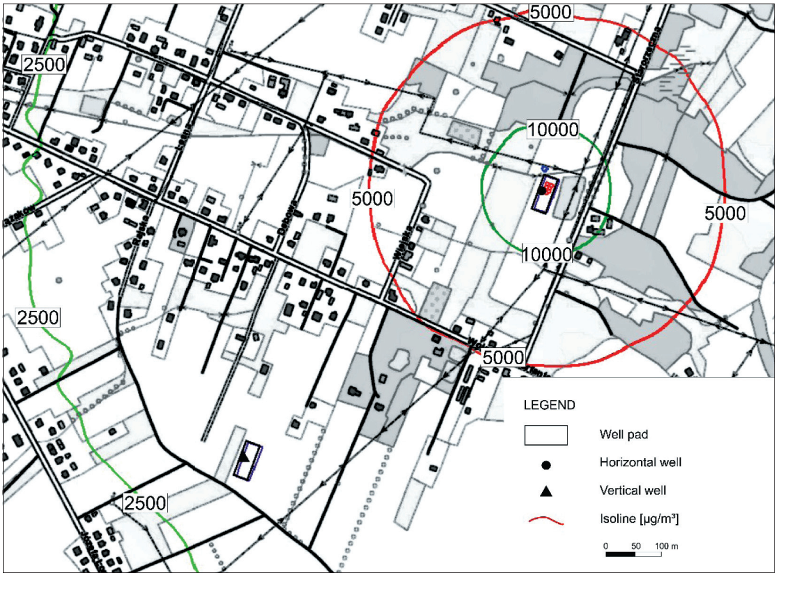

Fig. 4. Spatial distribution of NO_2 – maximum 1 hour NO_x concentration during hydraulic fracturing

Table 12 presents the results of the maximum annual concentration S_a and reference values for the year reduced by the background and their assessment in relation to legal requirements. Particulate matter, sulphur dioxide and nitrogen oxide met conditions specified in the full range of calculation.

Table 12

Calculation of pollutant concentrations in the full range

Pollutant	Calculated emission S_a	Average yearly concentrations reduced by the background value $[D_a - R]$	Evaluation
	[μg/m^3]	[μg/m^3]	
NO_2	3.45	20	$S_a < D_a - R$
PM10	0.094	15	$S_a < D_a - R$
CO	1.47	0	$S_a < D_a - R$

In Figure 5 graphical results of modeling the spread of pollutants in the air during hydraulic fracturing in relation to the maximum annual concentrations.

Fig. 5. Spatial distribution of NO_2 – maximum yearly NO_x concentration during hydraulic fracturing

Analysis of the results of calculations of the annual frequency of exceedances of substances in the air shows that the condition was met for all analyzed substances.

4. CONCLUSION

Methane from coal seam is extracted using the drilling technology. In order to increase extraction of methane, hydraulic fracturing operations should be carried out. These works should be carried out in such a way that air quality will not deteriorate. The results of modelling of propagation of contaminants during drilling and hydraulic fracturing operations shows that nitrogen oxides are the main substance that has a negative impact on air quality. In the case of using combustion engines to drive the drilling rig, air quality standards in the immediate area of their operation have not been met. The other pollutions generated during drilling and hydraulic fracturing operations do not create important hazard for the quality of air.

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