

Effect of Drilling for Shale Gas on the Quality of Atmospheric Air

Wpływ prac wiertniczych prowadzonych za gazem ziemnym w łupkach na jakość powietrza atmosferycznego

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Abstract

Shale gas is an alternative for conventional energy sources. When extracted in compliance with environmental and sustained development rules, it favors the concept of diversification of energy sources, giving spur to the development of economy and technology, and before all, to the energy safety of the country.

Poland is among countries, where expectations regarding shale gas are very high. Most of the exploration works for shale gas there are performed with the use of rigs, whose subassemblies are driven by electrical motors powered by mobile generators driven by diesel engines. The number of aggregates and their total power are selected each time on the basis of power balance of particular technological subassemblies and the emergency generation system. Diesel combustion motors used for powering generators are the only source of dust and gaseous emissions to the air. A mobile technological boiler room fed with oil is another source of emissions in the winter period. For the purpose of evaluating impact of rigs on the air environment in the course of prospecting for shale gas an emission model was worked out with five emission points. Four sources were connected with the operation of combustion motors (each 1257 kW) powering generators, and the fifth one (375 kW) feeding technological boiler room. The results of the tests on the environmental impact on motors and boiler room used during shale gas prospecting on the quality of air have been presented in the paper. The tests were performed with the use of mathematical modeling employing real technological data from existing installations.

Key words: drilling works, shales, shale gas, air quality, emission of pollutants, dust and gaseous pollutants, contamination of air, mathematical modeling

Streszczenie

Gaz z formacji łupkowych stanowi alternatywę dla konwencjonalnych źródeł energii. Wydobywany z poszanowaniem wymogów ochrony środowiska oraz w zgodzie z regułami zrównoważonego rozwoju jest elementem bezpieczeństwa energetycznego państwa, wpisuje się w logikę dywersyfikacji źródeł energii oraz stanowi impuls do rozwoju gospodarczego i naukowo-technicznego kraju.

Polska należy do krajów, w których z gazem łupkowym wiąże się duże nadzieje. Tutaj proces wiercenia otworów poszukiwawczych za gazem ziemnym w skałach łupkowych w większości przypadków prowadzony jest przy wykorzystaniu urządzeń wiertniczych, w których poszczególne podzespoły napędzane są silnikami elektrycznymi.

Jednak źródłem energii elektrycznej są dla nich mobilne zestawy generatorów napędzane silnikami wysokoprężnymi dużej mocy. Ilość agregatów oraz ich sumaryczna moc dobierana jest każdorazowo w oparciu o wykonany bilans mocy poszczególnych podzespołów technologicznych i systemu zasilania awaryjnego.

Wysokoprężne silniki spalinowe dużej mocy, wykorzystywane do napędu generatorów prądu, stanowią istotne źródło emisji zanieczyszczeń pyłowo-gazowych do powietrza. Ponadto w okresie zimowym dodatkowym źródłem emisji do powietrza jest mobilna kontenerowa kotłownia technologiczna zasilana olejem opałowym.

Dla potrzeb oceny wpływu pracujących urządzeń wiertniczych na jakość powietrza w trakcie prowadzenia prac poszukiwawczych za gazem ziemnym w skałach łupkowych, w stworzonym modelu emisyjnym założono pracę 5 punktowych źródeł emisji zorganizowanej. Cztery źródła są związane z pracą silników spalinowych, każdy o mocy 1257 kW, napędzających generatory, a piąty z pracą kotłowni technologicznej o mocy 375 kW.

W artykule przedstawiono wyniki badań wpływu na jakość powietrza silników spalinowych oraz kotłowni wykorzystywanych przy realizacji prac wiertniczych związanych z poszukiwaniem gazu ziemnego w skałach łupkowych. Badania prowadzone były metodą modelowania matematycznego w oparciu o rzeczywiste dane technologiczne pochodzące z obszaru wierceń poszukiwawczych.

Słowa kluczowe: prace wiertnicze, łupki, gaz z łupków, jakość powietrza, emisja zanieczyszczeń, zanieczyszczenie pyłowe i gazowe, zanieczyszczenie powietrza, modelowanie matematyczne

1. Introduction

Sustainable development refers to fulfillment of basic human needs. Since our civilization could not survive without energy it is no wonder that in a report called *Our Common Future* (WCED, 1987) energy was included among essential issues of sustainability. Since resources of traditional fossil fuels are shrinking, looking for alternative sources of energy is a must.

One of the alternatives to conventional energy sources is shale gas (Michałowski et al., 2012).

In this paper we present Polish experience. This is one of the countries, where expectations regarding shale gas are very high. The truth is, that when shale gas is extracted in compliance with environmental and sustained development rules, it favors the concept of diversification of energy sources, giving spur to the development of economy and technology, and before all, to the energy safety of the country. Regarding sustainability we must think however not only about exploitation of shale gas, but also about the environmental effects of drilling.

Shale formations with adsorbed or free natural gas are characterized by very low permeability and porosity. Therefore the efficient production of gas in such conditions requires using many multilateral directional wells and extensive fracturing jobs.

The drilling of opening wells starts with vertical sections in the caprock. The, above the roof of the shale strata, they are given the form of directional wells and long horizontal sections (about 2 to 3 km long) are drilled. About 20 fracturing jobs are performed in these sections to obtain a hydraulic connection between the rock and the well. Specialist drilling tools are used for this purpose. They are powered by high-pressure diesel engines of total power reaching up to a few thousands kW. For the sake of limiting the negative influence of drilling works on the environment, especially on the ground surface, 6 to 8 vertical wells are frequently drilled from one rig area and then 4 to 6 horizontal sections from each of them.

The risk analysis of drilling works referred to in (Zawisza et al., 2007; Rahm et al., 2011) reveals that the operation of diesel engines and mobile boiler room has most biggest impact on the air around the rig in the course of opening up operations. They emit large quantities of dust-gaseous pollutions, e.g.: nitrogen dioxide (NO₂), sulfur dioxide (SO₂), carbon dioxide (CO₂), carbon oxide (CO), dust PM₁₀ and PM_{2.5}, ammonia, methane (CH₄), benzo(a)pyrene (b(a)p), benzene, toluene, xylene, formaldehyde, acetaldehyde, acrolein.

The results of analyses of the effect of a combustion engine and a mobile boiler room on the quality of atmospheric air during shale gas prospecting have been discussed in this paper. The research was conducted with the use of mathematical modeling method based on real technological data from the area of Gdańsk Pomerania.

2. Identification of sources of emissions to the air

In Poland the process of performing exploration wells for shale gas is conducted with the use of drilling tools, the subassemblies of which are fed by electrical engines. The sources of electrical energy are mobile generators powered by high power diesel engines. The number of generators and their total power are selected each time on the basis of balance of power of particular technological subassemblies and the emergency generation system.

The high power diesel engines used for driving generators are a significant source of dust-gaseous atmospheric emissions (Macuda, Koniecznyńska, 2015). A mobile technological boiler room fed by fuel oil is another source of contamination in winter period. Owing to the high consumption of both diesel and fuel oil, they have to be stored in relatively capacious tanks in the rig area. These tanks can be another source of hydrocarbon emissions which can take place at the stage of reloading (huge tank breathing), storage (small tank breathing due to tempera-

Table 1. List of emission indices for engines over 560 kW fed with diesel oil (U.S. EPA, 2013)

Pollutant	Method of limiting emission	Fuel – diesel oil		
		Emission index referred to engine power (on output)	Emission index referred to energy introduced to engine with fuel ^{a)}	Quality of emission index ^{b)}
		[g/kWh]	[ng/J]	
NO _x	No	14.592	1376	B
	Delayed fuel injection	7.904	817	B
CO	No	3.344	365.5	C
SO _x ^{c)}	No	4.918 · S	434.300 · S	B
CO ₂ ^{d)}	No	705.280	70950	B
PM	Delayed fuel injection	0.426	43.0	B
TOC (as CH ₄)	No	0.429	38.7	C
Methane	No	^{e)}	^{e)}	E
NM VOC	No	^{e)}	^{e)}	E

^{a)} Indices calculated for engine powered by diesel oil of calorific value equal to 44 900 kJ/kg and density: 850.767 kg/m³.

^{b)} Quality of evaluation of emission index according to the scale: A - perfect, B – above average, C - average, D – below average, E - poor, F – no evaluation (no documented analyses).

^{c)} Index calculated for maximum sulfur content in diesel oil S [%].

^{d)} Assumed 100% conversion of C in fuel to CO₂.

^{e)} The analyses performed on only one engine revealed that the total organic carbon (TOC) measured in exhaust gases is based on methane in 9% and on non-methane volatile organic compounds (NMVOC) in 91%.

ture and pressure) and also during leaks of the fuel supply systems. The magnitude of the hydrocarbon emission from the tank is very low due to the low pressure of volatile vapor compounds of diesel and fuel oils. Therefore this emission was ignored in further analyses as negligible.

For the sake of analyzing the impact of operating rig on the quality of air during shale gas prospecting jobs, the emission model was equipped with 5 sources of emission (organized and point), associated with:

- emitters no. 1 – 4, emission from 4 combustion engines, each 1257 kW, driving generators,
- emitter no. 5 – emission from technological boiler room, 375 kW.

3. Quantitative calculation of emissions to the atmosphere

Emissions of dust and gases to the atmosphere in the rig area while drilling the vertical wellbore section and its horizontal off-springs are connected with the operation of diesel engines driving generators and a technological boiler room. This situation was accounted for in the model where the operation of 4 generators and a boiler room was assumed.

3.1. Dust and gas emission from diesel engines powering generators

The calculations of the emission of dust and gaseous substances from diesel engines powering the generators were performed on the example of a motor CATERPILLAR 3512B. This engine is most frequently applied for powering mobile generators

which are used in drilling industry. It has the following parameters (Caterpillar oil&gas, 2013): electric power: 1207 kW (1508 kVA), mechanical power: 1257 kW (1687 KM), fuel: diesel oil, cylinders: 12, constant number of rotations 1500 rpm, standard emission: U.S. EPA Tier 2, fuel consumption at 100% load: 293 dm³/h, 75%: 226 dm³/h, 50%: 159 dm³/h, temperature of exhaust gases at 100% load: 382 °C, 75%: 374 °C, 50%: 375 °C, exhaust gases flow rate at 100% load: 251 m³/min, 75%: 205 m³/min, 50%: 154 m³/min. It was assumed in the calculations that all 4 engines were of the same type.

When evaluating the atmospheric emission from diesel engines supplied by aggregates the following parameters were also taken into consideration: type and power of engine, type of substitute fuel, work characteristic (constant-speed, variable-speed), fuel consumption, treatment and emission-reduction systems, compliance to the emission standard. The US Environmental Protection Agency (U.S. EPA) in its document AP-42 (U.S. EPA, 2013) and the European Environment Agency (EEA) list emissions of substances introduced to the atmosphere by the analyzed engines in a database worked out within the project EMEP/CORINAIR (EEA, 2016). Table lists emission indices quoted after AP-42 (U.S. EPA) (U.S. EPA, 2013), which refer to engines of power over 560 kW, i.e. the ones described in the calculation example.

The analysis of table 1 reveals that the index of SO₂ emission depends on the percentage of sulfur (S) in the combusted fuel. According to the standard PN-EN 590 the sulfur content in diesel oil in Poland cannot exceed 0.001 wt.% (Polish Committee for Standardization, 2013).

A diesel engine emits aerosols of different chemical composition to the atmosphere. A qualitative and quantitative list of indices of aerosol emissions from a diesel engine (> 560 kW) with no emission-reduction system has been presented in table 2.

Table 2. Aerosol emitted by stationary diesel engine of over 560 kW, with no emission reduction system provided (U.S. EPA, 2013)

Contaminants	Emission index referred to energy introduced to engine with fuel [ng/J]
Fractions of analyzed solid particles ^{a)} :	
< 1 μm	20.554
< 3 μm	20.597
< 10 μm	21.328
Total amount of analyzed solid particles	26.66
Condensed liquid particles	3.311
PM ₁₀ ^{b)}	24.639
Total dust ^{c)}	29.971

a) The fractions interval is expressed as aerodynamic diameters of particles.

b) Sum of total measured dust particles of aerodynamic diameters < 10 μm and liquid condensed particles in the same fraction interval.

c) Sum of total measured dust particles and liquid condensed particles.

A diesel engine also emits volatile organic compounds (VOC) and polycyclic aromatic hydrocarbons (PAH). The emission indices for selected groups of compounds have been presented in tables 3 and 4, respectively.

Table 3. Emission indices of selected volatile organic compounds from stationary diesel engine (over 560 kW), with no emission reduction system provided (U.S. EPA, 2013)

Contaminants	Emission index referred to energy introduced to engine with fuel [ng/J]
Benzene	0.33368
Toluene	0.12083
Xylene	0.08299
Propylene	1.19970
Formaldehyde	0.03393
Acetaldehyde	0.01084
Acrolein	0.00339

When the engine is not equipped with any emission-reduction system, the indices listed in tables 1-4 should be used in predictions. The amount of the emission can be calculated on the basis of the power of engine in kW or amount and kind of fuel combusted in an hour. When the engine is equipped with treatment systems, the emission value should be corrected by the reduction degree obtained with a given treatment technique. The emission generated by engines, meeting certain emission limits, should be calculated with the use of boundary emission values presented in table 5.

Table 4. Emission indices of selected polycyclic aromatic hydrocarbons from stationary diesel engine (over 560 kW), with no emission reduction system provided (U.S. EPA, 2013)

Contaminants	Emission index referred to energy introduced to engine with fuel [ng/J]
Naphthalene	5.59E-02
Acenaphthalene	3.97E-03
Acenaphthene	2.01E-03
Fluorene	5.50E-03
Phenanthrene	1.75E-02
Anthracene	5.29E-04
Fluorantene	1.73E-03
Pyrene	1.60E-03
Benzo(a)anthracene	2.67E-04
Chrysene	6.58E-04
Benzo(b)fluorantene	4.77E-04
Benzo(k)fluorantene	9.37E-05
Benzo(a)pyrene	1.11E-04
(Indeno(1,2,3-cd)Pyrene	1.78E-04
Dibenz(a,h)anthracene	1.49E-04
Benzo(g,h,l)perylene	2.39E-04
Total PAH	9.12E-02

In the case of the analyzed type of engine, the following values should be accounted for in the emission calculations:

- for such contaminants as: carbon oxide (CO) and fine dust > 10 μm of grain size (PM10)
- from emission limits of U.S. EPA Tier 2 adequate to a diesel engine of power exceeding 560 kW (table 5),
- for hydrocarbons: from EPA guidelines AP-42 containing emission indices referred to the quantity of energy provided to an engine in fuel (tables 3 and 4),
- for nitrogen oxides (NO_x) – from EPA guidelines AP-42 containing emission indices referred to the power of engine (table 1),
- for carbon dioxide (SO₂) – from EPA guidelines AP-42 containing emission indices referred to the energy provided to the engine in fuel (table 1).

The calculation of hydrocarbon and sulfur dioxide emission based on emission indices referred to the amount of energy provided to the engine in fuel was performed for calorific value of diesel oil equal to 42.5 MJ/kg and density equal to 0.83 kg/dm³. In each case the calculations were performed for an engine loaded in 100%. For thus formulated assumptions and combustion of 293 dm³/h of diesel oil, the energy provided to the engine within 1 hr of its operation was calculated: 10 335.58 MJ/h. Knowing the energy provided to the engine with fuel, the hourly emissions of selected specific hydrocarbons, including polycyclic aromatic hydrocarbons (PAH), could be calculated. Their values have been given in tables 3 and 4. Then the annual emission of the analyzed hydrocarbons was calculated, assuming the duration of drilling vertical and horizontal sections on the

Table 5. Emission limits for diesel engines > 560 kW used, e.g. in pump aggregates (Dieselnet, 2016)

Contaminant	Emission limits in g/kWh			
	Tier 1	Tier 2	Tier 4 Interim	Tier 4
	2000-2005	2006-2010	2011-2014	+2015
CO	11.4	3.5	3.5	3.5
HC	1.3	-	0.4	0.19
NMHC+NO _x	-	6.4	-	-
NO _x	9.2	-	0.67	0.67
PM	0.54	0.2	0.1	0.04

Table 6. Emission of selected VOC emitted to air from engine powering generator

Contaminant	Emission [kg/h]	Emission [kg/year]
Benzene	0.00345	4.966
Toluene	0.00125	1.798
Xylene	0.000858	1.235
Propylene	0.01240	17.855
Formaldehyde	0.000351	0.505
Acetaldehyde	0.000112	0.161
Acrolein	0.000035	0.0504

Table 7. Hourly and annual emission of PAH emitted to air from engine powering the generator

Contaminant	Emission [kg/h]	Emission [kg/year]
Naphthalene	5.78E-04	0.83197
Acenaphthalene	4.10E-05	0.05907
Acenaphthene	2.08E-05	0.02995
Fluorene	5.69E-05	0.08192
Fenantren	1.81E-04	0.26111
Anthracene	5.47E-06	0.00787
Fluorantene	1.79E-05	0.02579
Pyrene	1.65E-05	0.02374
Benzo(a)anthracene	2.76E-06	0.00398
Chrysene	6.80E-06	0.00979
Benzo(b)fluorantene	4.93E-06	0.00710
Benzo(k)fluorantene	9.69E-07	0.00140
Benzo(a)pyrene	1.14E-06	0.00164
Indeno(1,2,3-cd)pyrene	1.84E-06	0.00265
Dibenzo(a,h)anthracene	1.54E-06	0.00221
Benzo(g,h,i)perylene	2.47E-06	0.00356
Total PAH	9.42E-04	1.35676

Table 8. Hourly and annual emission of NO_x, SO₂, CO, PM₁₀ and PM_{2.5} to air from one engine powering the generator

Contaminant	Emission [kg/h]	Emission [Mg/year]
NO _x	9.935	14.307
SO ₂	0.00449	0.00646
CO	4.400	6.335
PM ₁₀	0.251	0.362
PM _{2.5}	0.226	0.326

level of 60 days/year, i.e. 1440 hrs/year. The 1-hr and annual emissions of these substances have been listed in tables 6 and 7.

The SO₂ emission was calculated with the index method on the basis of calculated energy which was provided to the engine in fuel. The respective emission index used in the calculations has been presented in table 1. The maximum possible sulfur content in fuel, which is available on the Polish market, equals to %S = 0.001% (Polish Committee for Standardization, 2013). A 1-hr emission of NO_x, CO and PM (all of the emission is dust PM₁₀) was calculated as a product of respective emission indices (NO_x = 7.904 g/kWh, CO = 3.5 g/kWh, PM = 0.2

g/kWh) and power of engine (P = 1257 kW, at 100% load). For better illustration of the real noxiousness of the dust from the combustion motor an additional assumption was made that the dust emitted with exhaust gases contained 95% fractions of grain size < 2.5 μm (PM_{2.5}). The NO_x emission was calculated thanks to the emission index, which assumed that the engine was equipped with a system of fuel injection delay and did not have any exhaust gas treatment mechanisms. The results of calculation of the hourly and average annual emission for the assumed time of work of the engine (t = 1440 h/year) have been listed in table 8.

In the calculation of contaminants propagation each of the four concurrently operating engines will be an individual source of emission, which will have its own allotted point emitter labeled with the successive number (1-4).

3.2. Emission of dust and gaseous substances from the mobile Boiler room

In colder months the rig can operate only when the rooms of the crew are heated and the technological installations are protected against freezing.

It was assumed in the paper that the rig would be equipped with a mobile boiler room having the following parameters: boiler capacity: 375 KW, fuel: light fuel oil, calorific value of fuel: 42.6 MJ/kg, density of fuel: 0.86 kg/dm³, maximum sulfur content in fuel: 0.1%, energy efficiency of boiler: 90%, heat capacity: 1 350 MJ/h. The time of operation of the boiler room was assumed to be identical as the time of drilling vertical and horizontal section of the well, i.e. 60 days/year (1440 h/year). The least favorable emission variant was assumed, i.e. 100% load of the boiler room.

The calculation of suspended dust (PM₁₀), sulfur dioxide (SO₂), nitrogen oxides (NO_x expressed as NO₂) and carbon oxide (CO) was based on emission indices presented in the guidelines of the Ministry of Environmental Protection, Natural Resources and Forestry of April 1996: Emission indices for contaminants introduced to the atmosphere from the combustion of fuels (Ministry of Environmental Protection, Natural Resources And Forestry, 1996). The emission indices of basic substances emitted in the process of fuel oil combustion, referred to the quantity of burned fuel in m³, have been presented in table 9. The emission could be calculated on the basis of known hourly emission of fuel at 100% loading of the boiler room. This can be calculated from the formula:

$$B_{max} = \frac{100 \cdot Q_{max}}{W \cdot \eta \cdot \rho} \quad (1)$$

where:

B_{max} – maximum amount of combusted diesel oil at 100 % heat load of the boiler [dm³/h],

Q_{max} – maximum heat capacity at 100 % heat load of the boiler [kJ/h],

W – calorific value of light diesel oil [kJ/h],

η – energy efficiency of the boiler [%],

ρ – density of light diesel oil [kg/dm³].

Substituting values of particular entry data (already defined) authors could define the hourly consumption of light fuel oil on the level of 41 dm³/h. Having known the hourly fuel consumption and emission indices of the analyzed substances, the hourly emission of these substances could be calculated. The yearly emission was calculated on the basis of hourly emission and the assumed time of operation of the boiler room ($t = 1440$ h/year). The calculated values have been presented in table 9.

For the sake of the modeling, the mobile boiler room was assumed to have a point emitter no. 5.

4. Calculation of dispersion in air – methodology and assumptions

The effect of shale gas prospecting on the quality of air was assessed with the use of the gaussian model of contaminants propagation in atmospheric air. In Poland this model is recommended for evaluating the influence of emissions from point emitters on the air quality in areas of non-complicated orography. The evaluation was performed only for contaminants which had the strongest influence on the air, and for which admissible concentrations have been established in the Polish regulations, i.e.: PM₁₀, PM_{2.5}, NO₂, SO₂, CO and benzene. In this method the concentrations of the analyzed substances in air could undergo a comparative analysis with the admissible values. The remaining substances emitted to the air after the combustion of fuels in engines powering the generator and from the mobile boiler room, for which the emission values were established within the analyses, will not be taken into account because of their marginal impact on the concentration level. The following calculations were performed within the modeling procedure: maximum concentrations averaged for 1-hr (S_1), respective percentiles from 1-hr concentrations during a year ($S_{99.8}$) corresponding to admissible frequency of exceeding 1-hr reference values in air or admissible levels of substances in air ($P(D_1)$), average annual concentrations (S_a), dust precipitation on the ground surface (O_p).

The modeling was performed on the ground level ($z = 0$ m) in a regular grid of receivers localized at a distance of 50 m from one another. The calculation area had a square shape (1150 m side) and was defined in a local coordinates system. The rig was localized in the center of this area in the form of a square (150 m side). The analyzed sources of emissions were also placed in that area.

The assumed average coefficient of aerodynamic roughness of the surface for the assumed calculation area equaled to $z_o = 0.5$ m. The calculations made use of a 12-sector wind rose defined by the meteorological station in Gdańsk (Fig. 1).

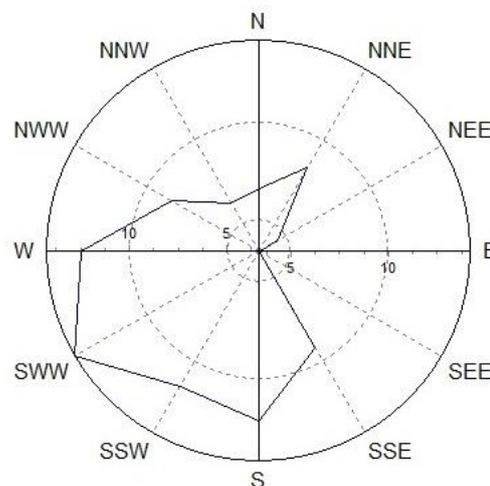


Figure 1. Annual wind rose plot for Gdańsk-Wrzeszcz

Table 9. Hourly and annual emission of PM₁₀, PM_{2.5}, SO₂, NO₂, CO, emitted to air from mobile boiler room

Contaminant	Emission index	Emission	
	[kg/m ³]	[kg/h]	[kg/year]
PM ₁₀	1.8	0.0738	106.272
PM _{2.5} *	1.35	0.0554	79.704
SO ₂	1.9	0.0779	112.176
NO ₂	5	0.205	295.2
CO	0.6	0.0246	35.424

* Emission index for PM_{2.5} calculated on the assumption that dust particles of diameter < 2.5 μm constitute only 75% of particles PM₁₀

Table 10. Coordinates of point emitters 1-5, their geometric parameters and parameters of exhaust gases

Emitter no.	Emitter	Emitter's coordinates		Height of emitter [m]	Diameter of emitter [m]	Temp. of gases [°C]	Velocity of gases [m/s]	C _p [kJ/m ³ ·K]
		X [m]	Y [m]					
1	Generator no. 1	590	530	4.0	0.35	382	43.5	1.40
2	Generator no. 2	590	525	4.0	0.35	382	43.5	1.40
3	Generator no. 3	555	530	4.0	0.35	382	43.5	1.40
4	Generator no. 4	555	525	4.0	0.35	382	43.5	1.40
5	Mobile boiler room	610	555	5.7	0.2	150	2.0	1.40

Table 11. Emission after 1hr from generators (emitters 1-4) and mobile boiler room (emitter 5)

Substance	Generators (emitters 1-4)	Mobile boiler room (emitter 5)
	[kg/h]	[kg/h]
NO ₂	9.93533	0.20500
SO ₂	0.00449	0.07790
CO	4.39950	0.02460
PM ₁₀	0.25140	0.07380
PM _{2.5}	0.22626	0.05535
Benzene	0.003449	-
Benzo(a)pyrene	0.0000011	-

The assumed coordinates of emitters, their geometrical parameters (geometric height of the emitter and its outlet diameter), parameters of exhaust gases (temperature, velocity flow rate on the emitter's outlet, specific heat of gases at constant pressure) have been presented in table 10. The parameters of emitters and exhaust gases were defined on the basis of real parameters of devices most frequently used in rigs.

The assumed hourly emission from 4 generators and a mobile boiler room have been listed in table 11.

5. Evaluation of the effect of shale gas prospecting on air quality

The results of calculations on the propagation of pollution in the atmosphere have been interpreted in line with the *Regulation of the Environment Minister of 24 August 2012 about the level of some substances in air* (Environment Minister, 2012) and *Regulation of the Environment Minister of 26 Jan. 2010 about reference values for some substances in air* (Environment Minister, 2010).

The admissible levels and reference values for the analyzed substances in air have been listed in table 12.

The reference/admissible 1-hr concentrations of suspended dust PM₁₀ and PM_{2.5}, NO₂, CO, as well as

benzene should not be exceeded more frequently than by 0.2% of the year, i.e. D₁ cannot exceed 99.8 percentile of 1-hr concentrations. In the case of 1-hr SO₂ concentrations the reference/admissible values cannot be exceeded more frequently than by 0.274% of the year (99.726 percentile of 1-hr concentrations).

The results of calculations of the analyzed substances in air, as referred to their reference/admissible values, have been listed in table 13.

All maximum 1-hr and maximum average annual concentrations were observed in one receptor of local coordinates X=600 m and Y=550 m and stayed within the rig area. From among the dust-gaseous substances emitted to the atmosphere only NO_x emission, calculated for NO₂, constituted a serious source of emission. In the case of 1-hr concentrations in the rig area the maximum values can reach even 1854 μg/m³ and the 99.8 percentile of these concentrations P(D₁) can be exceeded. The admissible value is not expected to go beyond the average annual concentration (D_a). All calculated maximum concentrations listed in table 13 were observed in the most unfavorable dispersion conditions, i.e. at stable or slightly stable state of atmospheric equilibrium. The spatial distributions of 1-hr concentration, the frequency of exceeding it and average annual concentrations from four generators and a mobile boiler

Table 12. Admissible and reference levels of analyzed substances in air [$\mu\text{g}/\text{m}^3$]

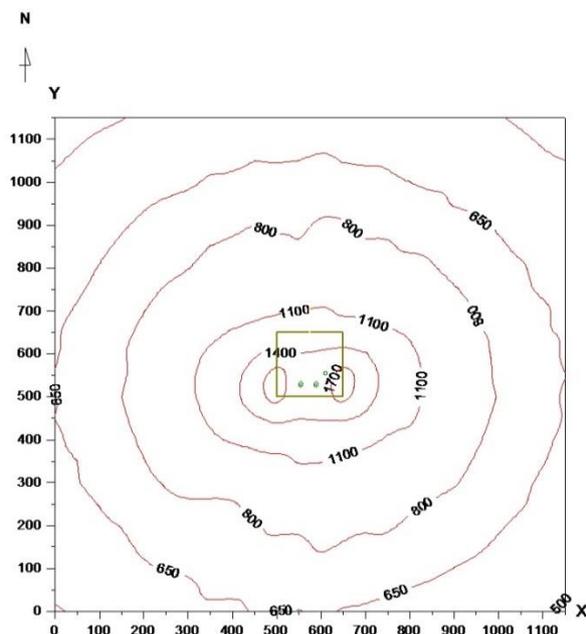
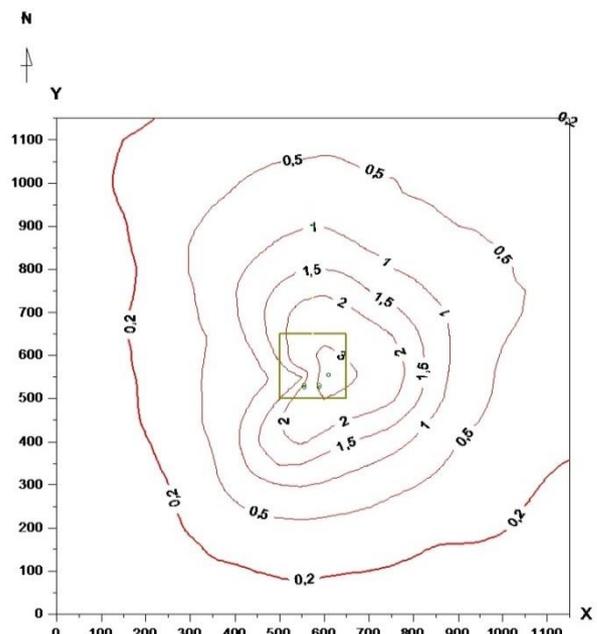
Contaminant	Validity	Admissible level after (Environment Minister, 2012) (reference value after (Environment Minister, 2010))	
		D ₁	D _a
PM ₁₀	-	(280)	40 (40)
PM _{2.5}	from 1 Jan. 2015 to 31 Dec. 2019	-	25 (-)
	from 1.01.2020	-	20 (-)
NO ₂	-	200 (200)	40 (40)
SO ₂	-	350 (350)	20 (20)
CO	-	(30000)	-
Benzene	-	(30)	5 (5)

Table 13. Calculated maximum concentrations after 1-hr and maximum average annual concentrations in air caused by emissions from 4 generators and mobile boiler room

Substance	Maximum concentration after 1-hr [$\mu\text{g}/\text{m}^3$]		Maximum frequency of exceeding D ₁ [%]		Maximum average annual concentration [$\mu\text{g}/\text{m}^3$]	
	Calculated	% D ₁	Calculated	Admissible	Calculated	% D _a
PM ₁₀	24.6	8.8	0	< 0.2	0.462	1.2
PM _{2.5}	21.9	-	0	< 0.2	0.404	1.6 ¹⁾
PM _{2.5}	21.9	-	-	-	0.404	2.0 ²⁾
NO ₂	1854	927.0	3.39	< 0.2	31.022	77.6
SO ₂	9.1	2.6	0	< 0.274	0.171	0.86
CO	820	2.7	0	< 0.2	13.603	-
Benzene	0.64	2.1	0	< 0.2	0.0106	0.21

¹⁾ % D_a referred to admissible concentration PM_{2.5} in air valid by 31 Dec. 2019

²⁾ % D_a referred to admissible concentration PM_{2.5} in air valid from 1 Jan. 2020

Figure 2. Spatial distribution of isolines of maximum concentrations after 1-hr presence of NO₂ in airFigure 3. Spatial distribution of frequency of exceeding maximum concentrations after 1-hr presence of NO₂ in air

room working at maximum capacity have been presented in figs. 2-4. The rig area was marked as a square in the calculation center.

The analysis of table 13 and figures 2-4 shows that the substance which may contribute to the exceeding of admissible concentrations in air in the course of shale gas prospecting is NO₂, whose high 1-hr concentration may extend far away beyond the rig area and be noxious for the environment. The analysis of

spatial distributions of isolines of maximum 1-hr and average annual concentrations of the remaining substances emitted from the analyzed sources revealed that in each case the concentrations of these substances will meet the standards for air beyond the rig area. The percentages of maximum 1-hr and average annual concentrations calculated for the most unfavorable emissions and meteorological conditions

equaled to 8.8 and 2% and did not exceed admissible/reference values.

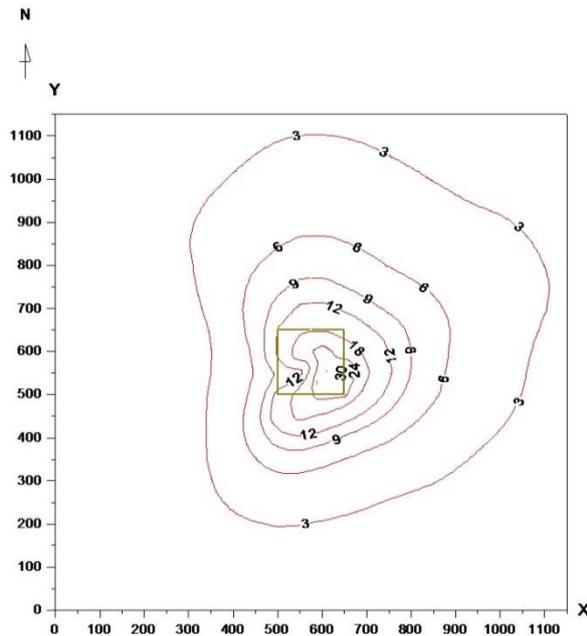


Figure 4. Spatial distribution of isolines of average annual NO_2 concentration in air

The maximum calculated value of dust condensation in the analyzed area totaled to $15.82 \text{ g/m}^2/\text{year}$, i.e. only 7.9% of the reference value ($200 \text{ g/m}^2/\text{year}$).

6. Conclusions

Apart from the preparation of the rig and fracturing jobs or hydrodynamic tests, drilling works constitute one of the major stages of shale gas prospecting. Modeling based on real data reveals that they are a significant hazard to the atmosphere because of the nitrogen oxides (NO_x) emissions. Such emissions are usually generated by high-power diesel engines powering the rig devices. A mobile boiler room is an additional source of NO_x emissions and also other contaminants. The modeling of dust-gaseous emissions from four diesel engines (1257 kW each) and a mobile boiler room (375 kW) showed that the NO_2 concentration in air beyond the rig area can be exceeded, especially in the periods of maximum load of the sources and bad conditions of propagation (state of constant equilibrium in the atmosphere, low speed of the wind). The remaining contaminants generated in the course of diesel and fuel oil in the analyzed sources do not create important hazard for the quality of air beyond the rig area.

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