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N. Yu. LUGOVTSOVA[1]*, Assistant, lnyu-70583@bk.ru*
S. S. TIMOFEEVA[2]*, Professor, Doctor of Engineering Sciences*
L. G. DEMENKOVA[1]*, Senior Lecturer*
A. V. FILONOV[1]*, Assistant*

[1]*Yurga Institute of Technology, Tomsk Polytechnic University, Yurga, Russia*
[2]*National Research Irkutsk State Technical University, Irkutsk, Russia*

STUDIES OF TOTAL HARMFUL GAS FLOWS ON THE GROUND SURFACE FROM SPONTANEOUS MINE FIRES IN KUZBASS*

The statistical analysis of air pollutant emission from stationary sources is carried out at large industrial centers in Kuzbass over the period from 2006 to 2015. The data on the active spontaneous fires in Kuzbass mines are reviewed. Emissions of harmful gases are studied using the land-based gas survey method. The total gas flow rate on the ground surface is evaluated. Based on the studies and calculations, the extra total toxic emission from active mine fires is determined.

Key words: *spontaneous fire, harmful gases, self-ignition processes, land-based gas survey, mined-out area, mine field, specific gas flow rate*

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Introduction

Practice shows that fires in mines are one of the main causes of accidents with casualties, material damage and environmental pollution. Among the mine fires, a special place belongs to spontaneous fires as a consequence of spontaneous ignition of coal accumulated in mined-out areas [1–3].

Spontaneous firing is sourced by coal accumulations and access of oxygen to oxidizing surface of broken coal. Coal accumulations may result from actual mining and form in coal bed damage areas. Rock pressure contributes to coal failure and accumulation at pillars left in mined-out areas. The outbreak and seats of such fires are difficult to reveal.

Underground fires greatly complicate production as fire fighting often ends with the loss of coal, roadways and expensive cutting-and-loading machinery. Spontaneous fires cause grave economic damage connected with fire extinguishing activities, reconstruction of damaged roadways and accident management.

Spontaneous firing is also accompanied by generation of large quantities of toxic gases propagating in mines and releasing from the ground surface. The gases releasing from the ground surface after spontaneous firing are mostly methane, carbon oxide, hydrogen, radon, etc. Around the combustion sources, moisture content of rocks drops, and convective air flows are formed, which contributes to the increase in dust escape in the atmosphere. The toxic gases and dust propagate over long distances from mining allotments and often at concentrations higher than maximum permissible limits set for the zones of working and residency [4, 5].

Such emissions are not always recordable. For example, mine accidents with fires and explosions result in major blowouts of toxic substances in the atmosphere. The suddenness of the events impedes the control and statistical recording of the blowouts. In the meanwhile, such blowouts are the considerable components in the general structure of the air pollutant emission.

The aim of this research is estimation of harmful gas flow rates from the ground surface above mines owing to spontaneous firing.

Theory

The issues of early detection of self-combustion have been studied by many researchers, in particular, by V. A. Skritsky, V. G. Igishev, N. I. Lindenau and V. A. Portol. The works [6–10] describe different methods to detect spontaneous fires at early stage. One of efficient self-combustion seat localization techniques is the control of tracer gases flowing from the ground surface [11–13]. Combustion gases (CH_4, CO, H_2) flow from mines and form a gas anomaly in the near-surface layer, this gas anomaly can be used in

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Table 1. Comparative analysis of gross pollutant emission at large industrial centers in Kuzbass within 10 year

Industrial center	Average emission for 10 years								
	Total emission, thou t	CH_4		CO		SO_2		NO_2	
		Quantity, thou t	% of total emission	Quantity, thou t	% of total emission	Quantity, thou t	% of total emission	Quantity, thou t	% of total emission
Mezhdurechensk	114.8	94.536	82.35	7.75	6.75	1.8	1.57	1.98	1.72
Leninsk-Kuznetsky	68.18	55.4	81.25	5.96	8.74	1.14	1.67	1.07	1.57
Belovo	70.46	9.6	13.62	8.38	11.89	14.74	20.92	9.6	13.62
Prokopyevsk	52.097	28.840	55.36	9.296	17.84	2.78	5.34	1.004	1.93
Kiselevsk	20.063	8.163	40.69	5.35	26.67	0.87	4.34	0.75	3.74
Novokuznetsk	337.09	28.24	8.38	210.34	62.40	36.22	10.74	17.87	5.27
Kemerovo	59.44	0.087	0.15	15.32	25.77	14.74	24.8	15.18	25.54
Kemerovo Region	1395.1	743.3	53.28	294.7	21.12	109.6	7.85	69.6	5

Table 2. Active fires in Kuzbass mines as of Jan 1, 2017

No.	Mine	Fire index	Fire development, dd.mm.yy	Fire cause	Date of sealing	Comments
1	Dzerzhinsky	851-2r	13.07.2009	–	No data	Fire foaming from ground surface
2	Dzerzhinsky	871	01.12.2010	–	–	–
3	Mine 12	449	22.04.2003	–	–	Passive extinguishing
4	Mine 12	456	26.11.2008	–	–	Fire fighting
5	Krasnogorskaya	856r	26.03.2010	–	–	–
6	Koksovaya-2	870	25.09.2010	–	–	–
7	Zenkovskaya	1 active fire				
8	Kiselevskaya	1 active fire				
9	Talda-Zapad	1 active fire				
10	Alarda	1	17.12.2002	External heat source	28.12.2002	Monitoring
11	Alarda	75	25.04.2005	External heat source	31.05.2005	Monitoring
12	Alarda	79	25.02.2011	Accumulation of methane-and-air mixture at an ignition source	06.03.2011	–
13	Lenin	55 ekz	18.11.1996	Smoking	03.06.1997	Monitoring
14	Lenin	23r	21.06.2001	Self-ignition of coal	28.06.2001	Monitoring
15	Raspadskaya	63 ekz	08.05.2010	Accumulation of methane-and-air mixture, ignitable coal dust	18.06.2010	Suppression by gaseous nitrogen, monitoring
16	Raspadskaya-Koksovaya	1 active fire				
17	Tomskaya	70	17.09.2012	Self-ignition of coal	12.02.2013	
18	Esaul	1 ekz	08.02.2005	Self-ignition of coal dust	14.02.2005	Monitoring
19	Polysaevskaya	3	07.09.2007	–	–	Monitoring
20	Voroshilov	378r	14.02.2009	–	–	Extinguishing from ground surface via holes

detection and localization of spontaneous fires. Such gas anomalies can be traced by land-based gas survey usually used in mineral exploration [14, 15]. However, literature lacks data on recording of gas emission quantities. As of today, there is a single method of over-land gas survey for the determination of quantity of harmful gas flows from the ground surface [16].

In the mean time, such gases make a substantial contribution to the unfavorable environmental situation in Kuzbass. The prevalent mine gas is methane generated as a result of metamorphism of vegetable substance. According to statistics, methane takes the first places in the general structure of the recorded emission from stationary sources in Kuzbass. Toxic carbon oxide gas is generated in large quantities during underground fires, failure and low-temperature oxidation of coal. For instance, during spontaneous firing under lack of oxygen in the air of mined-out roadway, carbon oxide concentration can reach 10–15% while the maximum allowable concentration of this gas in mine air is 0.0017%. If a combustible mineral contains sulfur admixtures, firing generates sulfur dioxide SO_2. This is a very toxic gas being one of the main components of volcanic gases. Underground mine fires also generate inflammable gas of hydrogen explosible at the content of 4–74% in the air.

Based on the analysis of the statistics given in the governmental reports on the state of environment in the Kem-

Alarda Mine field above the accident site of beds 1, 3 and 6 (scale 1:20000)

erovo Region, emission of major pollutants from stationary sources is estimated [17]. **Table 1** presents averaged data on the emissions in the largest industrial centers in Kuzbass for the period of 10 years from 2006 to 2015.

The analysis shows that the Kemerovo Region is an area exerting substantial anthropogenic load on environment. Out of all recorded emissions, methane emission prevails, discharge of CO and SO_2, is considerable, and some contribution is made by NO_2.

It is noteworthy that air quality monitoring in the area of Kuzbass is carried out at the stationary sites situated in Kemerovo, Novokuznetsk and Prokopyevsk (18 sites all in all).

Thus, a conclusion can be drawn that the estimation of quantities of gas flows on the ground surface from mine fields is incomplete. Currently, there are 20 recorded active spontaneous fires in Kuzbass. Some spontaneous fires can burn for years despite extinguishing measures [18, 19]. Frequent relapses of spontaneous firing are reflective of insufficient efficiency of fire fighting and sealing of roadways. **Table 2** gives information on active fires in Kuzbass mines as of January 1, 2017.

As is seen from the table, majority of spontaneous fires are caused by self-ignition of coal and coal dust. All active fires are in mines southward of the center of the Kemerovo Region, in particular, in Prokopyevsk, Novokuznetsk and Leninsk-Kuznetsk areas, as well as within Kaltan urban district.

For the estimation of the emission of spontaneous firing in mines, it is advisable to analyze harmful gas flows from mines by land-based gas survey.

Material and method of the research

To trace harmful gas flows from the ground surface, the land-based gas survey uses special reservoirs placed on the ground. The reservoirs have a diameter of 150 mm and a height of 90 mm. The edges of the reservoirs are buried in soil, and sampling of gases is carried out via a special pipe. Concentration of gases gradually increases in the reservoirs and is measured using a portable gas analyzer. The specific gas flow rate on the surface is calculated from the formula:

$$q = \frac{V_0 \cdot C}{S \cdot \tau_0}, \qquad (1)$$

where q — gas flow rate in the air, m^3/(s·m^2); V_0 — reservoir volume, m^3; τ_0 — pre-measurement standing period of the reservoir, s; C — gas concentration in the reservoir after the standing period, fraction; S — contact area of the reservoir and the ground surface, m^2.

According to the research [20], to measure specific gas flow rates on the ground surface, the reservoir standing period from 30 s to 5 min is sufficient. Thus, we take the standing period of 2 min (120 s).

To measure total gas flow from the surface of gas anomaly (potential fire site), it is required to divide the gas release zone into areas having approximately equal concentrations of harmful gas in the overland air layer. Then, the specific gas flow rate is calculated in an area using the formula (1). The total gas flow rate on the ground surface is given by:

$$Q_S = \sum_{i=1}^{n} q_i \cdot S_i\ , \qquad (2)$$

where n — number of gas release areas on the ground surface; q_i — specific gas flow rate in an i-th area, m^3/(s·m^2); S_i — size of the i-th area, m^2.

Discussion of the results

In the presented research, the land-based gas survey was carried out within the area of spontaneous fire no. 79 above an accident site of beds 1, 3 and 6 in Alarda Mine of Yuzhkuzbassugol company (**Figure**).

Check points were set in 12 cross-sections, total sampling size was 92. Measurement used the procedure from [16, 20] under the following conditions: time from 10 a.m. to 3 p.m., air temperature from 15 to 21°C, pressure from 742 to 744 mm hg. Overall test area on the ground surface made 300000 m^2. The contents of carbon oxide, hydrogen and methane in the air were determined using portable gas analyzer model APG-1.

The measurement data and the calculated flow rates of CO, H_2 and CH_4 are compiled in **Tables 3** and **4**, respectively.

The calculated total gas flow rate in the overall area of the ground surface above the mine using the formula (2) is presented together with the gross emission in **Table 5**.

Table 3. Measurement data on harmful gases in 12 cross-sections on the ground surface above the mined-out area of beds 1, 3 and 6 within the site of spontaneous fire no. 79 in Alarda Mine

Gas, %	Measurement data at test points																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Cross-section 1 (Overall length 800 m, sample size 17)																	
CO	0.001	0.004	0.001	0	0.0005	0.006	0.004	0	0	0.001	0	0	0.002	0.001	0	0	0.001
H_2	0	0.0008	0	0.008	0.003	0.05	0.0008	0	0	0.004	0.008	0.008	0.0008	0	0	0	0
CH_4	0.001	0.01	0.001	0.05	0	0	0.01	0	0.08	0	0.05	0.05	0.05	0.01	0	0	0.01
Cross-section 2 (Overall length 450 m, sample size 10)																	
CO	0	0.003	0.001	0.001	0	0.001	0	0	0.001	0							
H_2	0.008	0	0	0.004	0	0.001	0	0	0	0.008							
CH_4	0.1	0.06	0.01	0	0.05	0.08	0	0	0.01	0.1							
Cross-section 3 (Overall length 450 m, sample size 10)																	
CO	0.008	0	0.0005	0.002	0	0	0	0.01	0.002	0							
H_2	0	0.006	0.003	0	0	0.003	0	0	0.0008	0							
CH_4	0.2	0.05	0	0.2	0.08	0.01	0.08	0.01	0.05	0							
Cross-section 4 (Overall length 450 m, sample size 10)																	
CO	0.01	0	0.0005	0	0.001	0.001	0.001	0	0	0.0005							
H_2	0	0.01	0.003	0.003	0.001	0.004	0.004	0.006	0	0							
CH_4	0.01	0	0	0.05	0.08	0	0	0.05	0.05	0.01							
Cross-section 5 (Overall length 450 m, sample size 10)																	
CO	0.008	0.003	0.008	0	0	0	0	0.003	0.008	0.001							
H_2	0	0	0.001	0	0	0	0.005	0.001	0	0.004							
CH_4	0.2	0.06	0.005	0.008	0	0	0.3	0.001	0.02	0							
Cross-section 6 (Overall length 450 m, sample size 10)																	
CO	0.08	0	0.0035	0.0005	0.0022	0	0	0	0	0.001							
H_2	0	0.005	0.0008	0	0.002	0.0062	0	0	0.004	0.001							
CH_4	0.02	0.03	0.05	0.01	0	0.12	0.05	0.05	0.06	0.05							
Cross-section 7 (Overall length 400 m, sample size 9)																	
CO	0	0.009	0.001	0.002	0.002	0	0	0.001	0.003								
H_2	0	0.05	0	0.001	0.0008	0	0.0062	0.001	0.001								
CH_4	0	0.23	0.001	0.05	0.05	0	0.1	0.08	0.01								
Cross-section 8 (Overall length 350 m, sample size 8)																	
CO	0.001	0.003	0	0	0.002	0	0.001	0									
H	0.004	0.001	0	0.01	0.001	0.001	0	0.01									
CH_4	0	0.001	0	0	0.05	0.05	0.001	0									
Cross-section 9 (Overall length 700 m, sample size 15)																	
CO	0.001	0.001	0	0	0.001	0.002	0	0.006	0.006	0	0.008	0.004	0	0.0008	0		
H_2	0	0	0	0.016	0.001	0	0.006	0.001	0.01	0.0008	0.006	0	0.001	0.001	0.01		
CH_4	0.001	0.01	0	0	0.001	0.2	0.08	0.05	0.05	0.05	0.2	0	0.05	0.06	0		
Cross-section 10 (Overall length 700 m, sample size 15)																	
CO	0	0.001	0.008	0.0005	0.0006	0.001	0.001	0	0.003	0.001	0.001	0.001	0.006	0	0.001		
H_2	0	0.003	0	0.002	0.002	0.001	0	0.003	0	0.004	0.003	0	0.004	0.008	0		
CH_4	0.08	0	0.02	0	0.0001	0.008	0.01	0.01	0.06	0	0.01	0.001	0.05	0.005	0.01		
Cross-section 11 (Overall length 700 m, sample size 15)																	
CO	0	0.001	0.001	0.001	0.002	0	0.004	0.0035	0	0	0	0	0.0035	0.005	0.008		
H_2	0	0	0	0.001	0	0.016	0	0	0	0	0	0	0	0.001	0		
CH_4	0.08	0.01	0.01	0.05	0.02	0	0.05	0.06	0.08	0.08	0.05	0.05	0.06	0.05	0.02		
Cross-section 12 (Overall length 700 m, sample size 15)																	
CO	0.001	0	0.002	0.001	0.008	0	0.001	0	0	0	0.001	0.0022	0.0042	0.001	0.0005		
H_2	0	0	0.0008	0	0	0.01	0.004	0.006	0.004	0	0	0.002	0.0008	0	0		
CH_4	0.01	0.08	0.01	0.01	0.01	0	0	0.01	0.1	0.05	0.01	0	0.01	0.001	0.01		

Table 4. Specific flow rates on the ground surface above the mined-out area of beds 1, 3 and 6 within the site of spontaneous fire no. 79 in Alarda Mine

Specific gas flow rate, $q\cdot10^{-6}$, $m^3/(s\cdot m^2)$	Value at check points																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Cross-section 1																	
CO	0.075	0.3	0.075	0	0.037	0.45	0.3	0	0	0.075	0	0	0.15	0.075	0	0	0,075
H_2	0	0.06	0	0.6	0.22	3.75	0.06	0	0	0.3	0.6	0.6	0.06	0	0	0	0
CH_4	0.075	0.75	0.075	3.75	0	0	0.75	0	6	0	3.75	3.75	3.75	0.75	0	0	0,75
Cross-section 2																	
CO	0	0.22	0.075	0.075	0	0.075	0	0	0.075	0							
H_2	0.6	0	0	0.3	0	0.075	0	0	0	0.6							
CH_4	7.5	4.5	0.75	0	3.75	6	0	0	0.75	7.5							
Cross-section 3																	
CO	0.6	0	0.037	0.15	0	0	0	0.75	0.15	0							
H_2	0	0.45	0.22	0	0	0.22	0	0	0.06	0							
CH_4	15	3.75	0	15	6	0.75	6	0.75	3.75	0							
Cross-section 4																	
CO	0.75	0	0.037	0	0.075	0.075	0.075	0	0	0.037							
H_2	0	0.75	0.22	0.22	0.075	0.3	0.3	0.45	0	0							
CH_4	0.75	0	0	3.75	6	0	0	3.75	3.75	0.75							
Cross-section 5																	
CO	0.6	0.22	0.6	0	0	0	0	0.22	0.6	0.075							
H_2	0	0	0.075	0	0	0	0.37	0.075	0	0.3							
CH_4	15	4.5	0.37	0.6	0	0	22.5	0.075	1.5	0							
Cross-section 6																	
CO	6	0	0.26	0.037	0.16	0	0	0	0	0.075							
H_2	0	0.37	0.06	0	0.15	0.45	0	0	0.3	0.075							
CH_4	1.5	2.25	3.75	0.75	0	7.5	3.75	3.75	4.5	3.75							
Cross-section 7																	
CO	0	0.67	0.075	0.15	0.15	0	0	0.075	0.22								
H_2	0	3.75	0	0.075	0.06	0	0.46	0.075	0.075								
CH_4	0	17.25	0.075	3.75	3.75	0	7.5	6	0.75								
Cross-section 8																	
CO	0.075	0.22	0	0	0.15	0	0.075	0									
H_2	0.3	0.075	0	0.75	0.075	0.075	0	0.75									
CH_4	0	0.075	0	0	3.75	3.75	0.075	0									
Cross-section 9																	
CO	0.075	0.075	0	0	0.075	0.15	0	0.45	0.45	0	0.6	0.3	0	0.06	0		
H_2	0	0	0	1.2	0.075	0	0.45	0.075	0.75	0.06	0.45	0	0.075	0.075	0.075		
CH_4	0.075	0.75	0	0	0.075	15	6	3.75	3.75	3.75	15	0	3.75	4.5	0		
Cross-section 10																	
CO	0	0.075	0.6	0.037	0.045	0.075	0.075	0	0.22	0.075	0.075	0.075	0.45	0	0.075		
H_2	0	0.22	0	0.15	0.15	0.075	0	0.22	0	0.3	0.22	0	0.3	0.6	0		
CH_4	6	0	1.5	0	0.0075	0.6	0.75	0.75	4.5	0	0.75	0.075	3.75	0.37	0.75		
Cross-section 11																	
CO	0	0.075	0.075	0.075	0.15	0	0.3	0.26	0	0	0	0	0.26	0.37	0.6		
H_2	0	0	0	0.075	0	1.2	0	0	0	0	0	0	0	0.075	0		
CH_4	6	0.75	0.75	3.75	1.5	0	3.75	4.5	6	6	3.75	3.75	4.5	3.75	1.5		
Cross-section 12																	
CO	0.075	0	0.15	0.075	0.6	0	0.075	0	0	0	0.075	0.16	0.31	0.075	0.037		
H_2	0	0	0.06	0	0	0.75	0.3	0.45	0.3	0	0	0.15	0.06	0	0		
CH_4	0.75	6	0.75	0.75	0.75	0	0	0.75	7.5	3.75	0.75	0	0.75	0.075	0.75		

Table 5. Total gas flow rate on the ground surface above the spontaneous mine fire site in

Gas	Total flow rate, m^3/s	Gross emission, t/yr
CO	7.045	4856.5
H_2	8.838	437.6
CH_4	119.05	48806.7

Considering that there are 20 recorded spontaneous fires in Kuzbass, it can be assumed that the overall area on the ground surface above spontaneous firing can yearly emit 21 thou t of carbon oxide, 18.9 thou t of hydrogen and 210.5 thou t of methane. The total emission may make 250.5 thout t/yr.

Conclusions

Based on the research findings, some conclusions have been drawn:

1. The retrospective analysis of pollutant emission over the period of 10 years shows that the major contribution in the air pollution is made by methane emission (53%), substantial air pollution is made by carbon oxide (21%), emissions of sulfur dioxide and nitrogen are small — 8 and 5%, respectively.

2. According to the performed studies, 20 active spontaneous fires are recorded in mines in Kuzbass, some of these fires are active for years, and the cases of relapsed firing are known.

3. The surveys of harmful gas emission from the ground surface above the mine field show that a self-ignition site in one mine cam emit averagely 55 thou t of toxic substances per year. Accordingly, on the whole, the potential extra emission in the region may be round 250 thou t/yr, which makes 18% of the recorded gross emission at the stationary contamination sources.

The research findings can be used by environmental supervision and control specialists and by mine management for the recording of the additional emission from mine fires.

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