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Characterization of dust emissions from Shaft VI of the "Knurów–Szczygłowice" mine in the context of VAM utilization

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Abstract:

Ventilation air methane (VAM) from underground hard-coal mines is increasingly regarded as a potential fuel rather than an unavoidable waste stream. The feasibility of applying thermal or catalytic VAM oxidation technologies depends not only on methane concentration and volumetric flow rate, but also on dust loading, particle-size distribution, humidity, and the composition of the exhaust air. This paper presents original measurements carried out at Shaft VI of the "Knurów–Szczygłowice" mine (Szczygłowice section) within the ProVAM project as a potential site for VAM utilization. A three-stage program was implemented: short-term mapping across the exhaust diffuser cross-section, 24-hour measurements at a selected point, and week-long dust accumulation on a bag filter for compositional analysis. The measurements yielded relatively low mass concentrations of total dust (0.07–0.36 mg/m³), high relative humidity (85–95%), and a stable methane concentration of approximately 0.3–0.4 vol.%. Dust analysis indicated an average non-combustible (inert) fraction of 59.1%, implying a combustible fraction of about 41%. These findings are directly relevant to the design of VAM thermal oxidation units: they indicate that operation without front-end dedusting is feasible with appropriate bed design, while highlighting the need to address the risk of local hot spots and the impact of high humidity on process performance.

Keywords: ventilation air methane (VAM), hard-coal mine, mine dust, particle-size fraction, exhaust shaft, VAM oxidation

1. Introduction

Ventilation systems in underground hard-coal mines, in addition to supplying the required oxygen, ensure workplace safety by diluting and removing methane and other gaseous and particulate contaminants from active workings. A consequence of ventilation is the generation of substantial streams of ventilation air methane (VAM), which constitute a significant, diffuse source of methane emissions to the atmosphere. In contemporary greenhouse-gas mitigation approaches, VAM is increasingly treated as an energy carrier that can be utilized via appropriate oxidation technologies, rather than as a waste stream discharged without energy recovery [1, 2, 3, 4].

Selecting a VAM oxidation technology is a multi-criteria problem arising from the specificity of exhaust-shaft streams, which are characterized simultaneously by very high volumetric flow rates, low and variable methane concentrations (in Polish mines typically 0.01–0.43 vol.% [5]), high humidity (often near saturation), the presence of coal dust together with anti-explosive rock dust, and the potential presence of additional gaseous contaminants such as sulfur compounds. Although the majority of published data concern Polish hard-coal mines, comparable conditions have also been reported for underground coal mines in Romania, where ventilation air streams exhibit similarly low methane concentrations, elevated humidity levels, and variable dust loads resulting from geological conditions and mining practices. This indicates that the challenges associated with VAM utilization are not site-specific but representative of a broader group of Central and Eastern European coal basins. The quality parameters of exhaust air depend primarily on the scope of underground operations and on surface atmospheric conditions. Temporal variability of these parameters and their interactions substantially narrow the set of practically feasible technical solutions.

In engineering practice, two principal method groups are considered:

I. Enrichment of the gas mixture in methane (e.g., by adsorption, membrane techniques, cryogenic processes, or hybrid solutions).

II. Direct oxidation of VAM in thermal or catalytic units.

Despite intensive research, enrichment processes are associated with high unit costs and limited effectiveness at the very low CH_4 concentrations and extremely large volumetric flow rates typical of exhaust shafts [3]. For this reason, direct oxidation of low-methane mixtures is regarded as most promising, particularly in thermal flow reversal reactors (TFRR), which have seen industrial deployment at selected mining sites [4, 5, 6, 7].

Stable and safe operation of thermal or catalytic VAM oxidation systems requires fulfilment of several boundary conditions, including: ensuring the minimum methane concentration for autothermal operation, controlling the temperature profile within the bed, and providing tolerance to dust loading and high stream humidity. Dust present in VAM is a mixture of a combustible fraction (coal dust) and a non-combustible fraction (gangue, anti-explosive rock dust, and other inert materials). The combustible fraction can serve as an additional energy source in the reaction zone, but it also promotes the formation of local hot spots, which are particularly hazardous for catalytic beds with limited thermal stability ranges [8]. The mineral composition of dust, including sulfur content, can lead to accelerated catalyst deactivation and corrosive effects [9]. The employed bed geometry (e.g., monoliths with large channel cross-sections or ordered, high-permeability structures) should ensure unobstructed flow of the dust-laden mixture and minimize the risk of increasing pressure drop and channel blockage [7, 10].

Given these constraints, it was essential to obtain reliable, site-specific data characterizing VAM at a particular exhaust shaft, covering dust loading and particle-size distribution, the share of the combustible fraction in the dust, and the key gas parameters (CH_4 and O_2 concentrations, presence of contaminants). Shaft VI of the “Knurów–Szczygłowice” mine, Szczygłowice section (JSW S.A.), identified in the ProVAM project as a potential VAM utilization location [5], required such a detailed characterization.

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The objective of this study was to determine the mass concentration of total and respirable dust in the exhaust air from Shaft VI; to establish the particle-size distribution of dust in the ventilation air stream; to quantify the non-combustible fraction-and, by inference, the combustible fraction-of the emitted dust; and to relate the dust parameters obtained to the accompanying humidity, temperature, and methane concentration conditions.

2. Study site and methodology

2.1. Study site

The study was conducted at Shaft VI of the "Knurów–Szczygłowice" mine, Szczygłowice section (JSW S.A.), a peripheral ventilation shaft serving the interconnected workings of the Knurów and Szczygłowice sections, located on the outskirts of Knurów and Szczygłowice (Fig. 1). Air from the workings is conveyed to the Main Fan Station and subsequently discharged to the atmosphere through an exhaust diffuser. The current average airflow in the shaft is approximately 17,000 m³/min, with an average of about 22,000 m³/min forecast for 2024–2030.

Measurements were carried out under typical operating conditions on a representative working day, without any intervention in the main fan settings and without changes to the ventilation scheme. This approach ensured a VAM characterization corresponding to the shaft's actual operating conditions, which is crucial for the potential siting of a VAM utilization installation.

Fig. 1. View of the exhaust diffusers from Shaft VI of the "Knurów–Szczygłowice" mine [5]

2.2. Test program

A custom-designed test program was developed to quantitatively and qualitatively characterize the exhaust air from Shaft VI of the "Knurów–Szczygłowice" mine as a potential ventilation air methane (VAM) source for a planned thermal oxidation unit under the ProVAM project. The investigations aimed to determine total and respirable dust concentrations, particle-size distribution, the shares of combustible and non-combustible fractions in the dust, as well as selected gas parameters (CH_4, O_2, CO), and the humidity and temperature of the stream.

The program was structured in three stages, covering different time horizons and measurement precision:

1. Short-term grid measurements across the exhaust diffuser cross-section — to assess the uniformity of temperature, humidity, and dust loading fields, and to identify a representative point for continuous monitoring.
2. Continuous 24-hour measurements at the representative point — to record diurnal variability of total and fractional dust concentrations, particle-size distribution, and gas components (CH_4, O_2, CO).
3. One-week dust accumulation on a bag filter — to obtain a composite sample representative of typical shaft operating conditions, intended for analysis of the non-combustible fraction, combustible fraction, and sulfur content.

The measurement methodology was developed with reference to PN-EN 13284-1:2018 and PN-Z-04030-7:1994, with adaptations to the geometry of the Shaft VI diffuser and the study objective - i.e., characterization of VAM as a potential process medium for a thermal oxidation installation [11, 12].

2.3. Measurement equipment

A set of instruments was used to enable simultaneous monitoring of dust loading, physical air parameters, and gas composition, namely:

- IPS-Q analyzer — optical particle analyzer for measuring dust concentration and particle-size distribution over 0.4–300 μm (256 bins). Supports on-line data logging and measurement of flow velocity, air temperature, and relative humidity.
- DustTrak DRX 8533 — laser photometer for concurrent measurement of PM_1, $PM_{2.5}$, PM_{10} and total suspended particulates by light scattering; used to determine the fractional dust structure and to verify IPS-Q readings.
- CIP-10 personal dust samplers — personal gravimetric samplers for total and respirable dust concentrations. DRÄGER X-am 2500 — portable multi-gas analyzer for periodic measurements of CH_4, O_2, CO in the exhaust air stream; also used for safety monitoring during measurements.
- Ø250 mm bag-filter system — extraction setup for long-term (7-day) accumulation of dust from a partial exhaust stream. Samples were analyzed per PN-G-04037 to determine the non-combustible fraction, sulfur content, and combustible fraction.

3. Experimental procedure

3.1. Grid-point measurements

In the cross-section of the Shaft VI diffuser, a regular grid of measurement points was established, covering both near-wall regions and the core of the flow (Fig. 2). At each point, the following were performed:

- short-term measurements using the IPS-Q analyzer and DustTrak DRX photometer,
- measurement of flow velocity, temperature, and relative humidity (IPS-Q),
- control readings of CH_4, O_2, and CO concentrations using the DRÄGER X-am 2500 detector.

Based on the collected data, the degree of flow uniformity was assessed and a representative point was identified for long-term measurements.

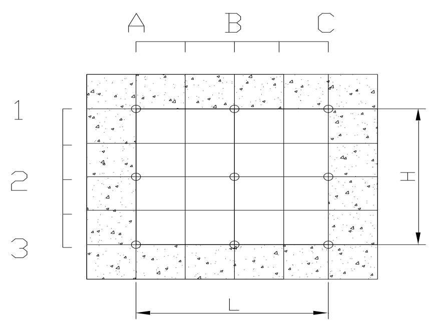


Fig. 2. Schematic layout of measurement points in the Shaft VI diffuser cross-section [5]

3.2. 24-hour measurements

At the selected representative point, a stationary measurement station was installed (Fig. 3), comprising:

- an IPS-Q analyzer operating in continuous mode with logging of 5-minute averaged values,
- a DustTrak DRX photometer recording PM fractions and total dust,
- periodic (hourly) control readings of CH_4, O_2, and CO using a DRÄGER detector,
- three parallel CIP-10 samplers performing 180-minute exposures to obtain reference gravimetric data.

The resulting dataset enabled analysis of the diurnal variability of dust loading and gas parameters, and their correlation with the shaft's operating conditions.

Fig. 3. Measurement station at the representative point of the Shaft VI diffuser [5]

3.3. Weekly measurements

After completion of the 24-hour series, a bag-filter system was started to extract a portion of the exhaust air stream (Fig. 4**Błąd! Nie można odnaleźć źródła odwołania.**). The exposure time was 7 days, which enabled collection of a dust sample representative of typical weekly shaft operation.

After exposure, the filter was dried, weighed, and submitted for laboratory analysis to determine:

- the non-combustible (inert) fraction,
- sulfur content,
- and, by inference, the combustible fraction.

The results provide a basis for assessing the nature of dust emitted from Shaft VI in terms of selecting the technology and construction materials for a future VAM thermal oxidation unit.

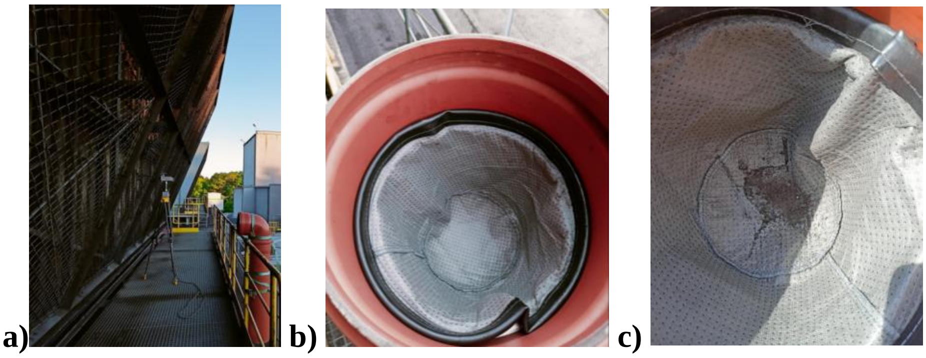


Fig. 4. Bag-filter system: a) installation location, b) filter condition before exposure, c) after 7 days of dust accumulation [5]

The adopted methodological solutions ensured both high spatial representativeness of the data and the ability to analyze the temporal variability of VAM parameters. Combining optical, gravimetric, and gasometric methods allowed cross-validation of results by different measurement techniques, increasing data reliability. Use of standardized procedures [11, 12] guarantees comparability with other underground-mining dust and gas emission studies.

4. Results

4.1. Characterization of the flow field and physical parameters

Short-term measurements in the diffuser cross-section of Shaft VI ("Knurów–Szczygłowice" mine) made it possible to determine the spatial variability of ventilation-air parameters. Based on the data (Fig. 5), the flow exhibited high uniformity—air velocity ranged from 2.9 to 6.0 m/s, with the lowest values in the upper zone. Knowledge of the outlet velocity in the diffuser is important for the design of the VAM take-off to a potential abatement system so as not to disturb the mine ventilation network.

Air speed [m/s]			
	A	B	C
1	2,90	3,10	3,00
2	6,00	6,00	5,90
3	5,00	5,00	5,80
Average value		4,74	

temperature [ºC]			
	A	B	C
1	25,3	24,8	24,6
2	25,3	25,3	25,1
3	24,6	26,6	24,4
average value		25,1	

humidity [%]			
	A	B	C
1	84,3	82,6	83,3
2	85,5	85,7	84,5
3	87,2	87,1	86,1
average value		85,1	

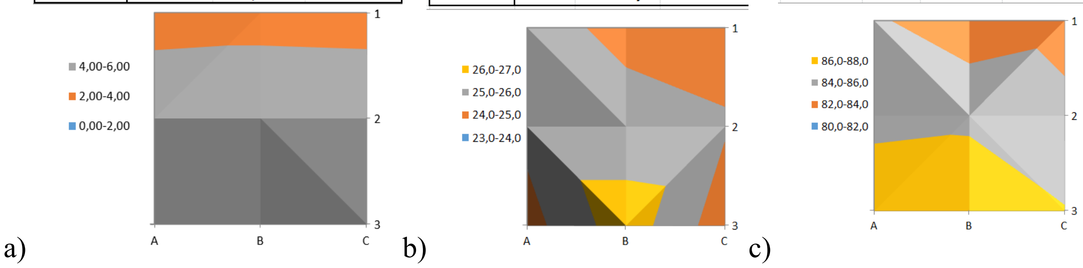


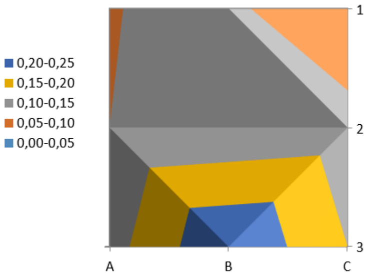
Fig. 5. Distributions in the Shaft VI diffuser cross-section: a) velocity, b) temperature, c) relative humidity [5]

Temperatures were 25–28 °C, while relative humidity remained high and stable at 82–87%. Humidity is critical for subsequent use of VAM in thermal or catalytic methane-oxidation reactors, as water-vapor contents exceeding 80% RH may shift the dew point and cause condensation in reactor components [13]. For catalytic reactors this effect is particularly unfavorable-water adsorbed on the catalyst surface blocks active sites and reduces oxidation performance [13, 14, 15, 16].

4.2. Ventilation-air dust loading

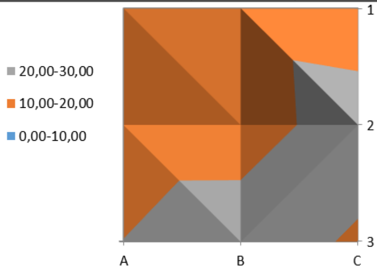
VAM dust loading is a key factor limiting stable operation of methane-oxidation units. IPS-Q measurements indicated a low average total dust concentration in the diffuser cross-section of 0.12 mg/m³, and an average Sauter mean diameter (D_{32}) of about 18 µm (Fig. 6). A similar concentration was obtained at the representative point, where the total dust level was 0.11 mg/m³.

Dust concentration [mg/m3]			
	A	B	C
1	0,10	0,11	0,06
2	0,10	0,11	0,12
3	0,13	0,25	0,15
Average value		0,12	



a)

Sauter D32 [µm]			
	A	B	C
1	17,60	13,10	9,90
2	12,00	12,10	28,60
3	20,20	28,80	17,90
Average value		17,80	

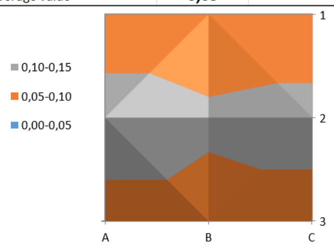


b)

Fig. 6. Grid-point measurement results: a) dust concentration, b) Sauter mean diameter (D_{32}) [5]

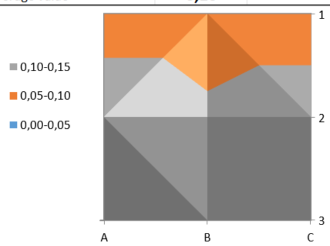
Parallel measurements with DustTrak DRX enabled determination of the shares of PM_1, $PM_{2.5}$, and PM_{10} (Fig. 7) and confirmed the average dust concentration on the grid consistent with IPS-Q. The average total dust concentration was 0.09 mg/m³, and 0.11 mg/m³ at the center point, confirming that point as representative.

PM1 (mg/m³)			
	A	B	C
1	0,06	0,06	0,06
2	0,13	0,11	0,12
3	0,08	0,08	0,08
Average value		0,09	



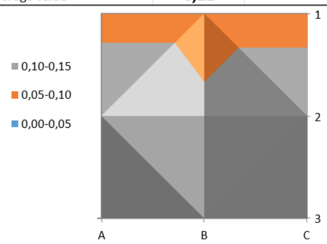
a)

PM2.5 (mg/m³)			
	A	B	C
1	0,07	0,07	0,07
2	0,14	0,11	0,13
3	0,10	0,10	0,11
Average value		0,10	



b)

PM10 (mg/m³)			
	A	B	C
1	0,08	0,08	0,08
2	0,15	0,11	0,14
3	0,11	0,11	0,10
Average value		0,11	



c)

Fig. 7. Distribution of particulate fractions in the Shaft VI diffuser cross-section: a) PM_1, b) $PM_{2.5}$, c) PM_{10} [5]

The $PM_{2.5}$ fraction accounted for about 70% of total mass, while PM_1 constituted about 40%. Such a high share of fine particles is typical of exhaust-shaft emissions from hard-coal mines [17] and indicates a respirable aerosol capable of penetrating porous structures of catalytic materials.

4.3. Gas composition of VAM

Gas-composition measurements with the DRÄGER X-am 2500 (Fig. 8) showed stable parameters across the grid: CH_4 = 0.30–0.41 vol.%, O_2 = 20.5–20.9 vol.%, CO = 2–3 ppm. No sulfur compounds (H_2S, SO_2) were detected, confirming good stream quality for thermal reactors. The methane levels obtained correspond to typical VAM in Polish mines (0.01–0.43 vol.%) [5].

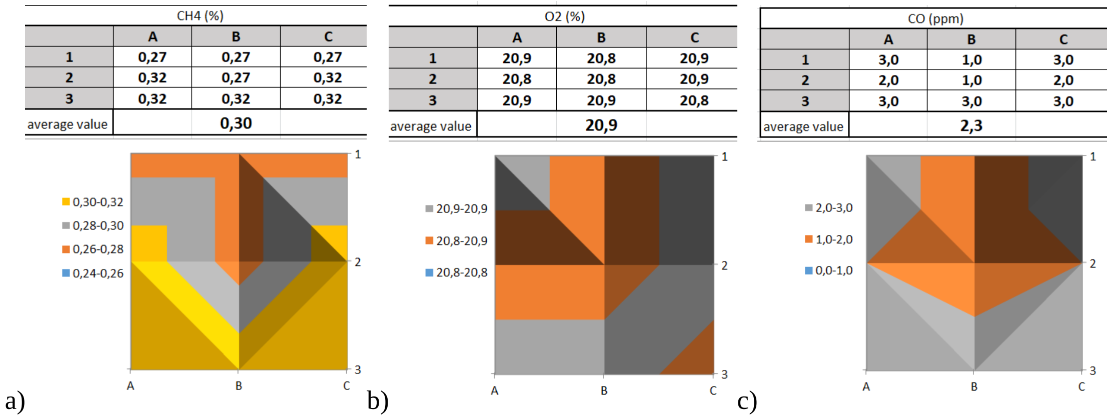


Fig. 8. VAM gas composition in the diffuser cross-section:
a) CH_4 concentration, b) O_2 concentration, c) CO concentration [5]

A CH_4 level of 0.3–0.4 vol.% is above the minimum threshold for thermal flow-reversal reactors (0.2–0.3 vol.% CH_4) and is sufficient for stable operation of the Dürr Oxi.X RV 62,500 Nm³/h reactor.

4.4. 24-hour measurements

Continuous monitoring at the representative point (Fig. 3) enabled assessment of diurnal changes in temperature, humidity, and dust loading (Fig. 9).

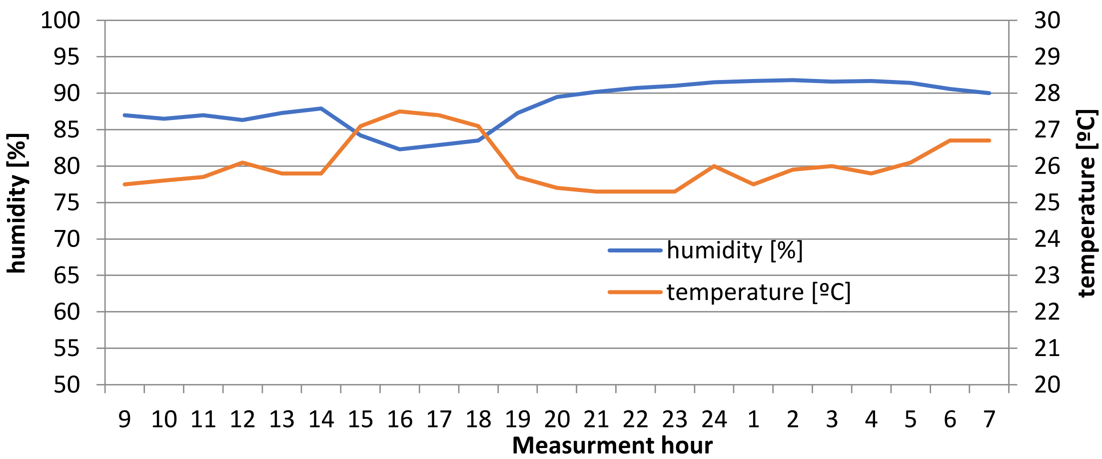


Fig. 9. 24-hour changes in air temperature and relative humidity [5]

Temperature remained within 25–28 °C, and RH within 85–95%, without a clear diurnal pattern. Drops in temperature of ~1 °C caused an increase in RH, indicating a constant absolute water content in the stream. The measurements also indicate that temperature and humidity remained stable regardless of changing outdoor atmospheric conditions.

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4.5. Diurnal variability of dust

Fig. 10 shows changes in total dust concentration and corresponding Sauter mean diameter (D_{32}) over 24 hours. Total dust ranged 0.08–0.36 mg/m³, while D_{32} reached 5–8 µm.

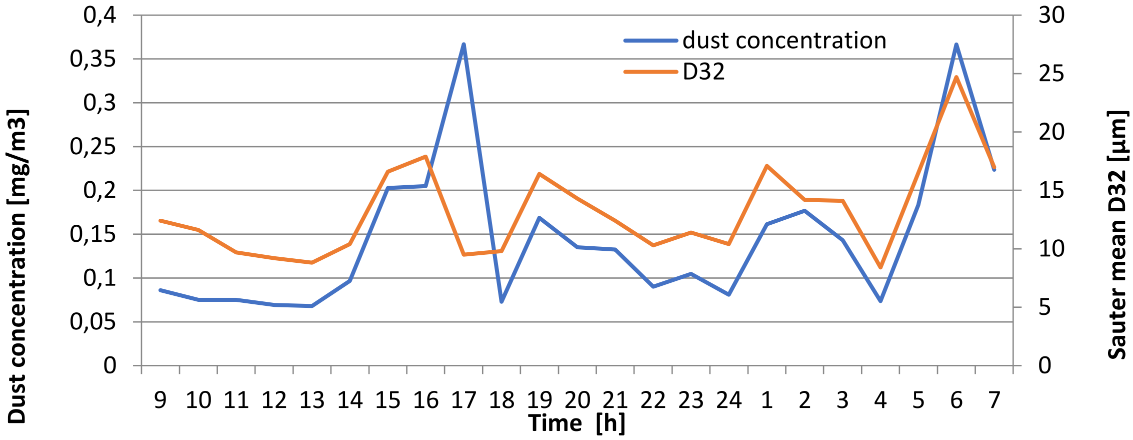

Fig. 10. 24-hour changes of total dust concentration and Sauter mean diameter (D_{32}) [5]

Particle-size distribution analysis (Fig. 11) showed that ~90% of particles by number had diameters < 7 µm, whereas isolated larger particles (up to 50 µm) accounted for as much as 25% of the total volume. This means that effective separation of the coarse fraction can significantly reduce mass dust loading with little effect on particle number in the aerosol.

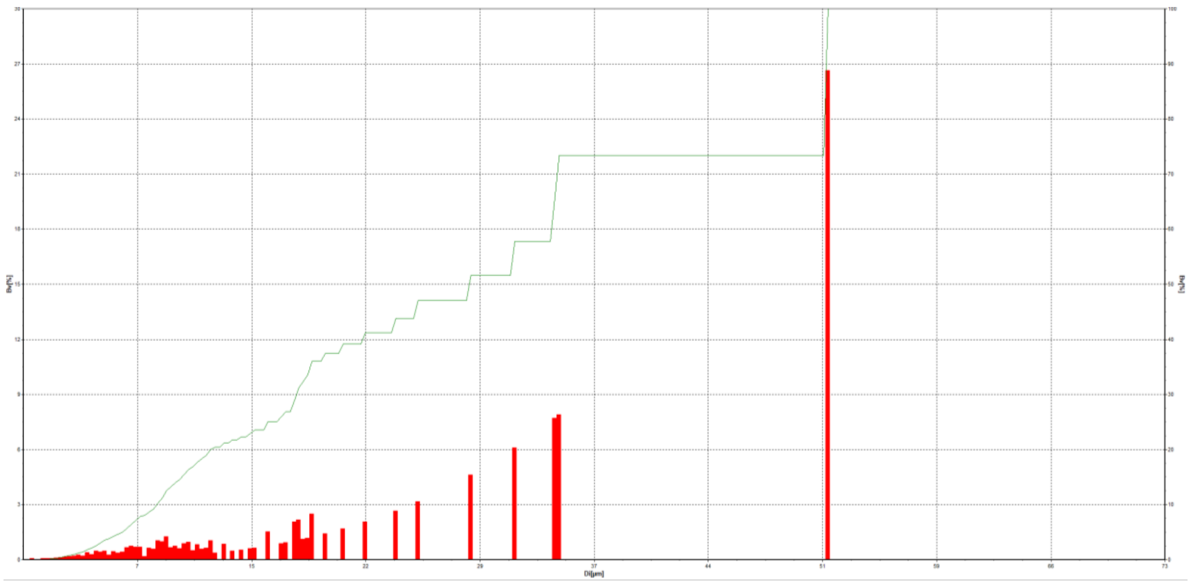

Fig. 11. Volumetric percentage share of dust fractions [5]

Averaged DustTrak DRX data (Fig. 12) confirmed the IPS-Q results and the dominance of $PM_{2.5}$ (0.16 mg/m³) and PM_{10} (0.22 mg/m³). The absence of significant diurnal anomalies confirms the stability of dust emission from exhaust shafts.

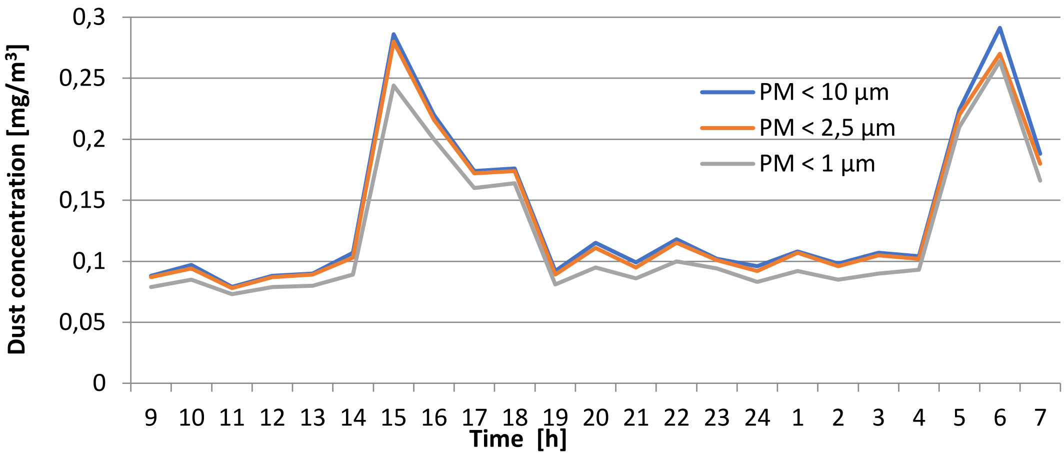

Fig. 12. 24-hour changes in PM_1, $PM_{2.5}$, and PM_{10} concentrations [5]

4.6. Gravimetric measurements and chemical analysis of dust

To validate the automatic dust-concentration readings, gravimetric measurements were performed between 3:00 and 6:00 pm using CIP-10 samplers at three points (Table 1).

The average mass concentration $\bar{S}$ was determined according to eq. (1):

$$\bar{S} = \frac{m}{\dot{V}\,\tau} \tag{1}$$

where:

m – dust mass collected by the sampler, mg,

$\dot{V}$ – volumetric air flow through the sampler, dm^3,

τ – exposure time, min.

The average total dust concentration for the measured period was 0.30 mg/m^3, and respirable dust 0.22 mg/m^3. Differences between points did not exceed 15%, confirming high uniformity across the diffuser cross-section. At the representative point, the 3-hour average was 0.25 mg/m^3, which corroborated the automatic instruments.

Table 1. CIP-10 results - total and respirable dust concentrations

Type of dust fraction	Mass Δm [mg]	Time [min]	Air flow [dm^3/min]	Dust concentration [mg/m^3]
Point B1				
total dust	0.62	180.00	10.00	**0.34**
respirable dust	0.33	180.00	7.00	**0.26**
Point B2				
total dust	0.45	180.00	10.00	**0.25**
respirable dust	0.21	180.00	7.00	**0.17**
Point B3				
total dust	0.57	180.00	10.00	**0.32**
respirable dust	0.29	180.00	7.00	**0.23**

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After completing the measurements, a bag filter (Fig. 4) was installed and operated for 7 days, enabling collection of a composite sample. Analysis per PN-G-04037 [18] showed a non-combustible (inert) content of 59.13% and sulfur of 0.231% (Table 2).

Table 2. Non-combustible and sulfur content in dust from Shaft VI

Sample	Non-flammable content	Sulfur content
S1	59.05	0.247
S2	59.33	0.236
S3	59.01	0.235
Average value	**59.13**	**0.231**

5. Discussion

The results allow several important conclusions regarding the characteristics of VAM from Shaft VI of the "Knurów–Szczygłowice" mine and its suitability for thermal methane oxidation. First, the flow-field mapping confirms a high degree of uniformity in both velocity and physical parameters (temperature, humidity). This is crucial for designing the VAM take-off to the reactor, as it ensures process-medium repeatability and reduces the risk of local transport disturbances.

The stable methane concentration of 0.30–0.41 vol.% falls within the range enabling autothermal operation of thermal flow-reversal reactors. This is a key feasibility criterion, since many prior analyses indicated that a large share of Polish exhaust shafts operate below the threshold. The results confirm that Shaft VI belongs to the most promising locations for future VAM abatement. Comparable methane concentration ranges have also been reported for selected Romanian mines, suggesting that the conclusions drawn here may be transferable beyond the Polish mining sector.

Dust-related findings are also of particular importance. Both optical and gravimetric measurements showed very low total and respirable dust concentrations relative to industrial reactor limits. Average total dust levels (~0.15 mg/m³ by IPS-Q and DustTrak) are more than an order of magnitude below limits defined. The measured inert fraction (59%), at such low concentrations, remains within Dürr allowances and should not negatively affect the lifetime of the reaction bed. Consequently, from the dust-loading perspective there is no need for front-end dedusting, which significantly simplifies the reactor design and reduces OPEX. Similar low-dust exhaust conditions have been identified in some Romanian shafts, particularly where intensive rock-dusting and effective dust suppression are applied.

A further point is the very high relative humidity (82–86%), stable throughout the measurement period. This parameter is critical during start-up, affecting dew-point shifts and temperature requirements for ignition. Under steady-state reactor operation, high humidity is not a hazard, but it should be considered in the heating system design and in condensate-risk assessment in ducting. Nevertheless, the recorded RH values do not indicate a need for additional air-drying modules.

Finally, the results confirm high repeatability of VAM dust and gas parameters in both the spatial (grid) and temporal (24-hour and weekly) domains. Such stability is uncommon in Polish mines and strongly supports selecting Shaft VI as a pilot location for methane-oxidation installation.

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