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Coal mine ventilation air emissions: project development planning and mitigation technologies

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ABSTRACT: Methane is a powerful greenhouse gas and the principal component of natural gas. Coal seams often contain significant quantities of methane, and underground coal mines must ensure that methane released into the mine during coal extraction does not build to dangerous levels. This is accomplished in part through the use of large-volume ventilation systems that remove methane from the mine and release it to the atmosphere. Although the methane concentration exhausted is quite low (typically < 1%), the volume of air that ventilation systems move is so great they constitute the largest source of methane emissions from underground coal mines. Each year, underground coal mines throughout the world emit more than 14 billion m^3 (500 billion ft^3) of methane from their ventilation systems. The global carbon market now offers an incentive for mitigating these emissions, in the form of carbon credits that constitute an additional revenue stream for gassy mines. There are an array of technologies that can be used to destroy ventilation air methane (VAM), including catalytic and thermal oxidation, gas turbines, and a hybrid waste coal/VAM rotary kiln. Thermal oxidation using a flow-reversal reactor has emerged as a tested and commercially available solution for VAM emission mitigation. If the technology is employed globally at active underground coal mines, it offers the potential to mitigate substantial quantities of methane emissions. In addition, oxidizers have the ability to tap the excess heat to produce steam for thermal uses or electric power generation. The following paper discusses global VAM emissions, VAM measurement requirements and recent shaft data for gassy U.S. mines. It also describes technology options for the recovery and utilization of VAM, as well as VAM projects in the United States, China, and Australia.

1 Introduction

Over geologic time, as organic sediments are converted to coal underground, methane gas (CH_4) can also be formed. Deep coal seams, especially those overlain by impermeable rock strata, can contain substantial quantities of methane gas that will be released into the mine during the coal extraction process. Because methane is explosive in concentrations between 5-15 % in air, such releases can present a serious safety problem for underground coal miners.

To maintain safe working conditions, the U.S. Mine Safety and Health Administration (MSHA) requires underground coal mines to employ large-scale ventilation systems that dilute methane. This is done to maintain in-mine concentrations well below the lower explosive limit and expel the methane in the mine out into the atmosphere. In addition, some mines are so gassy that they employ methane drainage systems. These systems directly extract methane from wells drilled into the coal seam itself or into the gob, the area of fractured rock that forms as the mine roof collapses following coal extraction. Methane drainage reduces the amount of gas in the coal and surrounding rock and therefore, less CH_4 is available to be released into the mine.

Although mine ventilation systems are effective in ensuring safe working conditions underground, they also create an environmental problem at the surface. Methane is a powerful greenhouse gas (GHG), with a global warming potential over 20 times that of carbon dioxide (CO_2) over a 100-year period. While mine ventilation exhausts contain methane in very low concentrations (typically below 1 %), the exhaust volume is quite large. In fact, methane emissions from gassy underground coal mines constitute the largest source of methane emissions from coal mines, and significantly contribute to global GHG emissions.

Methane is the principal component of natural gas and it can be used to fuel a host of useful applications. When methane is burned, it is converted to water and carbon dioxide, dramatically reducing its GHG impact. Methane captured by coal seam drainage systems (coal mine methane or CMM) may be of high quality and, in some cases, it can be directly injected into natural gas pipelines without requiring pre-treatment. Although gob gas is of lower quality than pre-mine drainage, it is nevertheless adequate for many direct-use applications. These include water heating, space heating, the firing of internal combustion engines or lean-fuel turbines and the upgrading of gas to meet pipeline specifications. In contrast, because of its very low concentration, the beneficial use of ventilation air methane (VAM) presents significant challenges. Nevertheless, there are technologies capable of processing VAM to reduce its GHG impact and capture its energy content.

2 VAM Monitoring

Measuring/monitoring VAM emissions (volume and concentration) is important in the context of VAM mitigation project implementation for two primary reasons. First, data characterizing VAM flows at active mines is needed to identify those mines that release VAM at levels adequate to support technically and financially sustainable projects. Second, in those instances where viable projects are implemented, the magnitude of VAM destruction over time must be quantified. This will provide a basis for documenting the energy generation and/or carbon credits that will constitute the project revenue streams.

2.1 U.S. VAM Data

Prospective project developers need to access data on VAM characteristics at multiple mines to identify a subset of mines that appear to offer good potential for profitable project development. A mine's ventilation exhaust airflow can be calculated from the ventilation fan size and capacity, or can be measured directly in the field; VAM concentrations must be determined by measurement. Federal regulations mandate that MSHA personnel conduct periodic safety inspections at underground U.S. coal mines, which involves measuring ventilation system airflow and methane concentration. Such inspections are performed annually at mines with emission rates less than 100,000 standard cubic feet per day (scfd), and quarterly for gassy mines with greater emission rates. Thus, review of MSHA quarterly sampling results can provide an initial determination of the subset of gassy mines that have exhaust airflows and methane concentrations high enough for VAM mitigation project development. The U.S. Environmental Protection Agency's Coalbed Methane Outreach Program performed a review of U.S. ventilation exhaust data for mines with VAM concentrations exceeding 0.3 percent. A summary of the results (by MSHA District) is presented in Table 1.

2.2 VAM Monitoring for Project Planning

Gassy underground coal mines routinely measure methane concentrations in and exiting the underground workings. In most cases, MSHA requires that such sampling be performed monthly at mines with methane emissions in the millions of cubic feet per day. For project planning and development purposes, however, sampling more frequently than monthly will be needed to gain a detailed understanding of flow and VAM concentration variability over time. While daily monitoring will provide a better perspective on the VAM characteristics at a given mine, sampling on an hourly or more frequent basis will provide the insight necessary to determine if:

a) a source of supplemental fuel will be needed to maintain an adequate methane flow in the equipment (e.g., thermal oxidizers) to sustain the process, or
b) ambient air will need to be bled into equipment to dilute high VAM concentrations, to ensure that equipment does not suffer thermal damage resulting from the release of excess heat of combustion.

2.3 Monitoring for Carbon Transactions

Methane monitoring to provide the documentation necessary to support the sale of carbon credits from VAM mitigation projects will likely have the highest requirement in terms of frequency. Such monitoring will need to be done on a timeframe that is sufficient to determine with a high degree of certainty the volume of methane destroyed by a project over time. It is expected that third-party verifiers will determine the sampling record frequency that is necessary for a given project to meet their oversight needs. Projects may employ some form of continuous monitors to track methane concentrations, so that adjustments in concentration (i.e., either up or down) can be made in real-time to maintain safe operation of the processing equipment. The required monitoring record of methane destruction can be captured from such monitoring systems.

3 VAM Mitigation Technology Options

The first field use of VAM (in 1996) was as combustion air for internal combustion (IC) engines powering electricity generation at the Appin Colliery in New South Wales, Australia. The project employs 54 VAM/CMM driven internal combustion engines to produce 55.6 MW of electricity for the mine (see Figure 1). In that application, VAM constitutes a supplemental fuel, contributing fuel input to the IC engines. Using ventilation exhaust as combustion air in large boilers (e.g., utility or industrial) has also been demonstrated on a pilot scale at the Vales Point Power Station in Australia. Such applications are limited by the need to site the facility near the mine to efficiently divert VAM to the boiler. In contrast, the much smaller IC engines are readily deployable at remote locations.

Another supplemental fuel approach is employed by EESTech Inc., who acquired the rights to an innovative rotary kiln system (developed by Australia's Commonwealth Scientific and Industrial Research Organization - CSIRO) that burns waste coal with VAM (or drained coal mine methane). The mixed fuel is combusted in a rotating kiln and the exhaust gas passes through a specially designed air-to-air heat exchanger. The hot, clean air then powers a turbine to produce electricity. The waste coal feed can be adjusted as necessary in response to variations in VAM flow or concentration, thereby allowing for a constant energy feed to the turbine to power electricity generation. EESTech is currently

Table 1 Summary of MSHA 2008-2009 quarterly sampling data

MSHA District	Parameter	<100,000 cfm	100,000-199,999 cfm	200,000-299,999 cfm	300,000-500,000 cfm	500,000-1,000,000 cfm	>1,000,000 cfm
2	# Exhausts	2	6	8	0	1	1
	CH_4 Range	0.30-0.35	0.31-0.40	0.43-1.09	-	0.34	0.30
3	# Exhausts	0	7	8	5	1	0
	CH_4 Range	-	0.43-1.26	0.36-1.25	0.30-1.23	0.33	-
4	# Exhausts	2	1	1	4	0	0
	CH_4 Range	0.70-0.85	0.4	0.97	0.31-0.69	-	-
5	# Exhausts	0	0	0	3	0	0
	CH_4 Range	-	-	-	0.44-1.06	-	-
7	# Exhausts	0	0	0	1	0	0
	CH_4 Range	-	-	-	0.36	-	-
8	# Exhausts	1	5	4	0	4	0
	CH_4 Range	0.43	0.32-0.83	0.45-0.50	-	0.21-0.37	-
9	# Exhausts	0	0	0	1	4	0
	CH_4 Range	-	-	-	0.35	0.39-0.55	-
10	# Exhausts	0	1	0	0	0	0
	CH_4 Range	-	0.31	-	-	-	-
11	# Exhausts	0	0	1	3	3	0
	CH_4 Range	-	-	0.41	0.31-1.11	0.35-0.93	-

Note : Districts 1 and 6 have no mines reporting VAM concentrations exceeding 0.3%.

Figure 1 Appin power plant.

seeking to commercialize the technology in China and India.

Lean-fuel turbine systems can also be adapted for VAM utilization in instances where drained CMM is available to boost the concentration of VAM exiting the mine. For example, CSIRO has developed the VAMCAT™, a gas turbine that employs a catalytic combustor to run on VAM concentrations in the 1% range. A 30 kW demonstration unit is planned to be tested at the Huainan Mining Group's Panyi Mine in China.

Similarly, California-based FlexEnergy offers the Flex-Microturbine™ that is capable of using methane concentrations as low as 1.5%. Microturbines are combustion turbines that are rated to produce power in the range of 1 MW or less, normally sized between 30kW to 250 kW. Combustion turbines combine an upstream compressor and a downstream turbine with a combustion chamber located in between. Fuel enters the chamber, where it is combusted to drive the downstream turbine and generate electricity. FlexEnergy developed a 100 kW prototype that was sent to a landfill-gas-to-energy project in February of 2010. Their smallest production model will be 250 kW. The system takes in fuel at atmospheric pressure and is capable of destroying not only the methane in the feed, but also moisture and other contaminants. The only constituent that may cause a problem is sulphur, which can be corrosive and lead to the formation of sulphur dioxide (SO_2). In proof-of-concept testing, their system was shown to achieve nearly full power running on fuels equivalent to < 2% CH_4. In both the VAMCAT and FlexEnergy lean-fuel technologies, VAM is the principal fuel and drained CMM is supplemental.

In addition, technology that has been employed for years in industrial air pollution applications has proven viable in VAM mitigation applications. Flow-reversal oxidizers, which can be either thermal or catalytic, are commercially available and capable of oxidizing even low VAM concentrations. When VAM enters an oxidizer, it encounters a bed of heat exchange material that has been preheated to the oxidation temperature of methane (1000°C or 1832°F). The VAM oxidizes and releases heat, which in turn maintains the temperature of the heat transfer material at or above 1000°C, thereby sustaining the auto-oxidation process over time (without requiring supplemental fuel input). Valves and dampers repeatedly reverse the flow of incoming VAM to keep the zone in the center of the oxidizer hot (Figure 2).

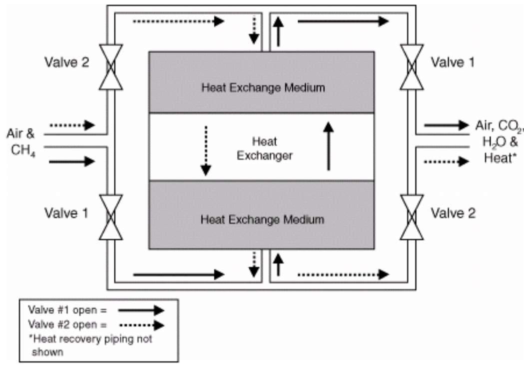

Figure 2 Basic flow-reversal oxidizer schematic.

Both catalytic and thermal systems operate on this principal, although catalysts in the heat exchange medium allow the reaction to occur at lower temperatures. Flow-reversal oxidizers can be used solely to destroy methane without heat recovery, in which case the only revenue stream is from the sale of carbon emission reduction credits. Alternatively, the heat of combustion can be captured and used for thermal energy (e.g., space or water heating) or to power electricity generation. In such heat recovery applications, revenues would derive from both carbon credit sales as well as the value of the captured energy (heat or electricity). Note, however, that most heat recovery applications would mandate the use of the thermal flow-reversal reactor (TFRR) rather than the catalytic flow-reversal reactor (CFFR) to maximize economic returns, since the former generates more heat (and thus extracts more value in terms of energy recovery) from a given VAM flow than does the latter.

4 VAM Technology Vendors

As mentioned above, VAM oxidation technology is an adaptation of one category of industrial air pollution control equipment. Each of the North American VAM oxidizer vendors discussed below brings extensive experience in designing systems to address a variety of pollutants. Although new to VAM abatement, their history of industrial air pollution control facilitates the transitioning of their equipment to meet conditions in the field at coal mines. To date, two of these vendors (MEGTEC Systems and Biothermica) have demonstrated the efficacy and performance of their TFRR systems at coal mines. Those projects are described in Section 5.

4.1 MEGTEC Systems

MEGTEC Systems (DePere, Wisconsin) entered the VAM sector in 1994, by modifying its TFRR to fit VAM mitigation applications. The configuration of their design, the VOCSIDIZER™, is essentially the same as that illustrated in Figure 2. MEGTEC manufactures standardized units with an inflow capacity of 125,000 m^3/hour. For applications requiring larger capacity, individual VOCSIDIZER™ units can be coupled together.

4.2 Biothermica

The Canadian firm Biothermica (Montreal, Quebec) offers the VAMOX™ technology. While it employs the same operating principal as that illustrated in Figure 2, its design is slightly different in that its two heat exchange beds are configured side by side and both connect with an overlying plenum that serves as a reaction chamber. In operation, the incoming flow passes through one heat exchange bed, into the reaction chamber, and out through the other bed, following which the direction of flow reverses, still passing through the plenum in each cycle. Biothermica custom designs each of their installations to meet site-specific conditions.

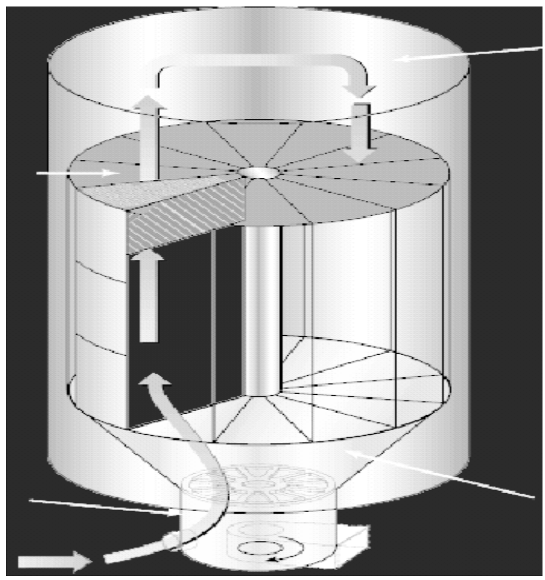

Figure 3 Dürr Ecopure® RL rotary RTO.

4.3 Dürr Systems, Inc.

Dürr Systems (Plymouth, Wisconsin) has a unique rotary oxidizer design (Figure 3), which uses a single rotating valve to direct the inflowing air through a series of oxidation chambers. Air enters and passes through one reactor chamber, flows out of that chamber into and through a plenum at the top, and exits the unit by flowing through another reactor chamber on the opposite side. The inflow/outflow chambers are switched as the valve rotates. Dürr's Ecopure® RL rotary regenerative thermal oxidizer (RTO), which avoids the use of poppet valves and dampers to control the flow-reversal process, has been proven in industrial applications over the past decade but has yet to be field-tested in VAM-oxidation applications.

4.4 Gulf Coast Environmental (GCE)

Recently Gulf Coast Environmental (Willis, Texas) began building on their experience in the field of industrial air pollution control to offer their TFRR (Figure 4) for VAM mitigation applications. The GCE VAM Model oxidizer design actuates the flow-reversal process using a single valve through which ventilation air passes twice. This results in a low pressure drop in the system. In addition, it includes a hot gas bypass that eliminates damaging buildup of excess heat in the oxidation core when unacceptably high concentrations of methane occur in the ventilation exhaust entering the oxidizer.

Figure 4 GCE VAM Model oxidizer.

4.5 CANMET

Canada's Centre for Mineral and Energy Technology (CANMET – Ottawa, Ontario) has developed and pilot-tested a CFRR design, termed the CH_4MIN, which is specifically intended for VAM applications. Their technology has not yet been deployed in VAM mitigation applications, but it is in the process of being commercialized by SCS Americas in countries that signed on to the Kyoto Protocol. SCS built a 15 m^3/s test unit (Figure 5) and is in the process of executing design modifications based on the results obtained. They plan to have initial units operating in China in the near future.

4.6 Sheng Dong Group

In addition to the North American technology vendors/designers introduced above, China's Sheng Dong Group (Dong Ying City, Shandong Province) also has a traditional TFRR design (Figure 6). The Sheng Dong oxidizer received its Chinese patent in May of 2007.

Table 2 summarizes key operating parameters and the deployment status of the various systems described above.

Figure 5 CH_4MIN 15 m^3/min. test reactor.

5 Chronology of VAM Oxidation Projects

A number of TFRR field demonstration and commercial projects have been performed since the early 1990s. The emergence of this technology through those projects is described below.

5.1 MEGTEC Projects

MEGTEC has been the clear pioneer in VAM oxidation technology development. Their project history began in 1994 when the VOCSIDIZER™ was first demonstrated at British Coal's Thoresby Mine in Nottinghamshire, United Kingdom. That project successfully proved the TFRR's ability to sustain operation on mine exhaust flows under actual field conditions.

Following the success of the Thoresby demonstration, a modified VOCSIDIZER™ was deployed at the Appin Colliery in 2001-2002. The Appin demonstration built on the Thoresby experience by including an internal heat recovery subsystem to tap the excess heat of combustion for boiling water. Operating over a 12-month period, that project proved that the system would perform reliably even with variations in VAM flow typical at active underground coal mines. This successful project demonstrated the potential for TFRRs to be used for a variety of energy applications, such as thermal energy or electricity generation.

Table 2 VAM Technology Comparison.

VAM Technology	Capacity (valued rounded)	Minimum VAM Concentration Requirement (%)	Methane Removal Efficiency (%)	Deployment Status
CH4MIN	900 m^3/h (530 scfm)	0.15	95	Laboratory testing using natural gas
Ecopure® RL	6,287-101,952 m^3/hr (3,700-60,000 scfm)	0.2	99	History of industrial VOC control applications
EESTech HCGT	5-30 MW power output	TBD	TBD	Unknown
Flex-Microturbine™	6,243 m^3/hr (3,674 scfm) for 250kW unit	3 - 5	99 (target)	Pilot/demonstration at landfill
GCE CH_4 Model	84,960 m^3/hr (50,000 scfm)	0.25	95	History of industrial VOC control applications
Sheng Dong Oxidizer	60,000 m^3/h (35,316scfm)	0.25	95	Industrial VOC installation in China
VAMCAT	TBD	1.0	TBD	Unknown
VAMOX™	up to 169,920 m^3/h (100,000 scfm)	0.2	98	History of industrial VOC control applications; ongoing commercial VAM-oxidation project in U.S.
VOCSIDIZER™	125,000 m^3/h (73,575 scfm)	0.2	97	History of industrial VOC control applications; ongoing commercial VAM-to-power project in Australia.

Figure 6 Sheng Dong Oxidizer.

Building on the success of that second demonstration project, MEGTEC joined with BHP Billiton to construct and operate a full-scale VAM-to-electricity project at the West Cliff Colliery in New South Wales (Figure 7). Dubbed WestVAMP (West Cliff Ventilation Air Methane Project), the project started operation in April 2007. It consumes approximately 1/5th of the mine's total ventilation system exhaust to feed a processing capacity of 250,000 m^3/h (147,150 scfm) of ventilation air. The VAM contains 0.9%CH_4, with that concentration being maintained by combining drainage gas with the mine's ventilation exhaust flow. The project integrates MEGTEC VOCSIDIZER™ units with a conventional steam turbine.

The system, running on superheated steam from the TFRR, generates 6 MW of electrical power (which is fed to the mine). WestVAMP continues to operate and, as of August 2009, the project had generated 80,000 GWH of power and created 500,000 Australian carbon credits (New South Wales Greenhouse Gas Abatement Certificates).

Figure 7 WestVAMP project.

To provide the North American mining industry with tangible evidence of the VOCSIDIZER's™ effectiveness, MEGTEC teamed with CONSOL Energy to conduct a field demonstration project at the abandoned Windsor Mine in West Liberty, West Virginia (Figure 8). Since it is an abandoned mine, drained methane was mixed with air to obtain a methane-in-air blend that is typical of VAM from an active mine. The project, which operated from February 2007 through October 2008, employed a single VOCSIDIZER™ unit to process ~50,000 m^3/h (29,430 cfm) of simulated VAM, at a concentration of 0.6%CH_4.

The Windsor project provided hands-on domestic experience in operating a VAM oxidizer, verified VAM destruction efficiency, and confirmed system safety and operation under U.S. field conditions. It provided proof of the system's ability to oxidize the low concentration of methane typical of many underground coal mine exhausts, and determined the amount of useful energy that TFRRs can produce.

Figure 8 Windsor Mine Project.

Recently, Green Holdings, a greenhouse gas abatement company, announced that it has partnered with CONSOL Energy to develop what will be the largest VAM abatement project in the U.S. The project will be sited at the Enlow Fork mine in Pennsylvania and is projected to mitigate 190,000 tCO_2e/yr. The specific oxidizer technology to be employed has yet to be specified.

5.2 Biothermica Project

Joining with Jim Walter Resources (JWR), Biothermica developed a small-scale commercial project at an active underground mine. Biothermica designed and installed a VAMOX™ unit at JWR's Mine No. 7 in Brookwood, Alabama (Figure 9). That project employs a single VAMOX™ unit that oxidizes 51,000 m^3/h (30,019 cfm) of 0.8%CH_4 VAM. The project was initiated in January 2009 and it is the first to operate at an active mine in the Americas. It also is the first VAM oxidation installation to receive approval from the U.S. MSHA. As this is an oxidation-only project (i.e., does not include energy capture and use), its revenues derive solely from the sale of carbon offset credits during the planned 4-year operational lifetime.

In February of 2010, Biothermica announced that the project had been listed with the Climate Action Reserve (CAR), making it the first CMM project to achieve listing in this offsets program. The project is in compliance with Version 1.0 of CAR's Coal Mine Methane Project Protocol. During its initial year of operation, the project generated 27,000 carbon credits that will be registered with CAR for sale in the North American market. In subsequent years, it is expected to reach an annual 35,000 credit level.

Figure 9 Jim Walter Resources Mine Project.

6 Conclusions

A number of technological options exist for mitigating flows of VAM from gassy underground coal mines. Prospective project developers will base their technology selection decision on a number of factors, with VAM flow and concentration being of paramount importance. Therefore, in seeking and evaluating the attractiveness of VAM project opportunities, mine-specific VAM monitoring data will be critical. While annual or quarterly sampling results can be useful in conducting a screening-level evaluation of prospective project sites, more frequent sampling will be needed to fully plan a project's operational parameters. When carbon transactions are involved, extensive sampling will be necessary to support verification of the methane destruction achieved over time by a project

To date, the flow reversal oxidizer has emerged as a proven solution for VAM mitigation applications. Currently, four vendors are offering oxidizer designs specifically for VAM mitigation applications, two of which have conducted field demonstrations and commercial projects. With an expanding carbon market in the U.S. and accepted project methodologies available (such as that developed by CAR), substantial opportunity now exists for managers of gassy underground coal mines. Every year, new technological developments are taking place to better utilize VAM, an otherwise wasted by-product of coal mining operations. VAM emissions can now be transformed into an additional revenue source, while also contributing meaningfully to global climate change mitigation.