PROGRESS IN DEVELOPING VENTILATION AIR METHANE MITIGATION AND UTILISATION TECHNOLOGIES

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ABSTRACT

This paper reviews the existing and developing technologies for coalmine ventilation air methane (CH_4) mitigation and utilisation, particularly the field of CH_4 oxidation, with respect to technical feasibility, engineering applicability, and potential to recover the heat released from CH_4 oxidation.

Ventilation air methane contributes approximately 64% of coalmine CH_4 emissions, and is difficult to use as an energy source, as the air volume is large and the methane resource is dilute and variable in concentration and flow rate. The low concentration of methane in mine ventilation air is a major problem, and mitigation requires either treatment in its dilute state, or concentrating up to levels that can be used in conventional methane fueled engines. Effective technology for increasing the concentration of methane is not available but it is being developed, and most work has focussed on the oxidation of very low concentration methane. These processes may be classified into thermal oxidation and catalytic oxidation in terms of combustion kinetic mechanism. Utilisation technologies for ventilation air methane generally divide into two basic categories: ancillary uses and principal uses. For the ancillary uses, ventilation air is used as a substitute for ambient air in combustion processes, including gas turbines, internal combustion engines and coal-fired power stations. For the principal uses, methane in ventilation air is a primary fuel. The variation in methane concentration and flow in mine ventilation air impacts significantly on the effectiveness of mitigation and utilisation technologies.

1 INTRODUCTION

Fugitive methane, emitted from coalmines around the world, represents approximately 8% of the world's anthropogenic CH_4 emissions that constitute 17% contribution to anthropogenic emissions. China ranks number one in world coal production and is responsible for about 45 percent of the total ventilation air CH_4 emissions [1]. At a typical gassy mine methane is emitted in three streams: (1) mine ventilation air (0.1-0.7%CH_4), (2) gas drained from the seam before mining (60-95% CH_4), and (3) gas drained from worked areas of the mine e.g. goafs (30-95% CH_4). Ventilation air methane contributes approximately 64% of coalmine CH_4 emissions, and is the most difficult to use as an energy source, as the air volume is large and the methane resource is dilute and variable in concentration and flow rate. The low concentration of methane in mine ventilation air is a major problem, and mitigation requires either treatment in its dilute state, or concentrating up to levels that can be

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used in conventional methane fueled engines. Effective technology for increasing the concentration of methane is not available but it is being developed, and most work has focussed on the oxidation of very low concentration methane. These processes may be classified into thermal oxidation and catalytic oxidation in terms of combustion kinetic mechanism. Utilisation technologies of ventilation air methane generally divide into two basic categories: ancillary uses and principal uses. For the ancillary uses, ventilation air is used to substitute ambient air in combustion processes, including gas turbines, internal combustion engines and coal-fired power stations. CSIRO intends to develop a process where waste coal and methane in ventilation air are expected to burn in a rotating kiln to generate electricity by using externally fired gas turbine system. For the principal uses, CH_4 in ventilation air is a primary fuel. These processes include MEGTEC thermal flow-reversal reactors (TFRR). CANMET catalytic flow-reversal reactors (CFRR), EDL recuperative gas turbine, CSIRO lean burn catalytic turbine, and CSIRO catalytic combustor (CMR) which could be combined with coal drying, or heating/cooling possibly with an adsorption chiller. The main limitation of TFRR and CFRR systems is that it is difficult to extract useful energy for power generation, so they generally only mitigate most of the greenhouse impact of the methane. The CSIRO catalytic turbine powered with 1% CH_4 is more prospective technology to both mitigate the methane and generate electricity. 1% methane can be obtained by combining mine ventilation air methane and drainage gas at a gassy mine.

This paper reviews the existing and developing technologies of coalmine ventilation air methane (CH_4) mitigation and utilisation, particularly in the field of CH_4 oxidation, with the respects of their technical feasibility, possibility of recovering heat released from CH_4 oxidation, and engineering applicability. The variation in methane concentration and flow in mine ventilation air impacts significantly on the effectiveness of mitigation and utilisation technologies.

2 TECHNOLOGY CLASSIFICATION AND CH_4 OXIDATION MECHANISMS

2.1 TECHNOLOGY CLASSIFICATION

Classification of ventilation air CH_4 mitigation and utilisation technologies is presented in Table 1 so that one could easier understand differences of the technologies in terms of fundamental mechanisms, technical principles, applicability.

2.2 CH_4 OXIDATION MECHANISMS

The combustion mechanism of methane may be overall represented by the following equation.

$$CH_4 + 2O_2 = CO_2 + 2H_2O \quad \Delta H_{(298)} = -802.7 \text{ kJ/mol}$$

This is a gross simplification, since the actual reaction mechanism involves many free radical chain reactions [2]. The combustion of methane may produce CO or CO_2 depending on the air/methane ratio by the reactions.

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

$$CH_4 + 3/2O_2 = CO + 2H_2O$$

Other reactions may also be present, such as:

$CH_4 + H_2O = CO + 3H_2$
$2H_2 + O_2 = 2H_2O$
$CO + H_2O = CO_2 + H_2$

Table 1 Technology classification

Technology	Oxidation mechanism	Principle	Application
Ancillary uses			
Combustion air for conventional pf power station	Thermal	Combustion in pf power station boiler furnace	Mitigation Utilisation – demonstrated in a pilot-scale unit, and being considered for a full-scale demonstration
Combustion air for gas turbine/engine	Thermal	Combustion in conventional gas turbine/engine combustor	Mitigation Utilisation – not demonstrated yet
Hybrid waste coal/ tailing/methane combustion in a kiln	Thermal	Combustion inside a rotating combustion chamber	Mitigation Utilisation – being trialled in a pilot-scale unit
Hybrid waste coal/ tailing/methane combustion in a fluidised bed	Thermal	Combustion inside a fluidised bed and freeboard	Mitigation Utilisation – being proposed as a concept
Principle uses			
Thermal flow reverse reactor (TFRR)	Thermal	Flow reverse reactor with regenerative bed	Mitigation – demonstrated Utilisation – not demonstrated yet
Catalytic flow reverse reactor (CFRR)	Catalytic	Flow reverse reactor with regenerative bed	Mitigation – demonstrated Utilisation – not demonstrated yet
Stand-alone catalytic combustor (monolith)	Catalytic	Monolith reactor with a recuperator	Mitigation – demonstrated Utilisation – not demonstrated yet
Catalytic lean burn gas turbine	Catalytic	Gas turbine with a catalytic combustor and a recuperator	Mitigation – combustion demonstrated Utilisation – being developed in a lab-scale unit
Recuperative gas turbine	Thermal	Gas turbine with a recuperative combustor and a recuperator	Mitigation – demonstrated Utilisation – demonstrated in a pilot-scale unit, and need for further modifications (?)
Concentrator	N/A, adsorption	Multi-stage fluidised/moving bed using adsorbent, and a desorber	Mitigation Utilisation – under development

Studies of the kinetic mechanisms of methane catalytic combustion can become quite involved when multi-step surface reactions are considered. Chou et al. [3] used 23 different reactions in their numerical study of methane catalytic combustion in a monolith honeycomb reactor. The situation becomes even more complicated when considering heterogeneous reactions. Figure 1 shows a possible mechanism for methane catalytic oxidation proposed by Oh et al. [4].

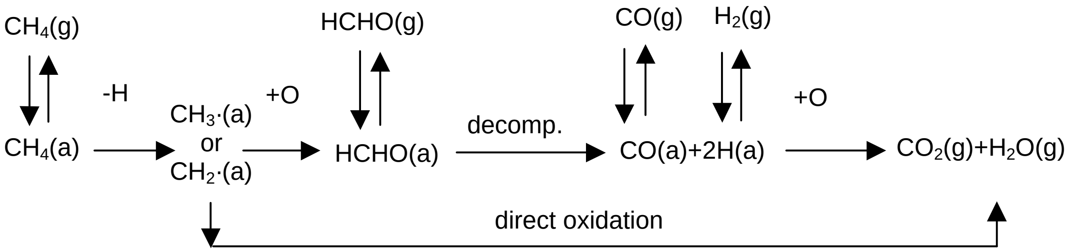

Figure 1 A possible mechanism for methane catalytic oxidation [4]
(a) adsorbed, (g) gas phase

In general, catalytic combustion is a multi-step process involving diffusion to the catalyst surface, adsorption onto the catalyst, reaction, and desorption of the product species from the catalyst surface and diffusion back into the bulk. Most kinetic investigations have been performed in conditions where methane is present in excess of the stoichiometric ratio. The result of this is that the reaction has generally been found to be independent of the oxygen concentration. The reaction order with respect to methane is generally found to be between 0.5 and 1 [2]. Lee *et al.* [2] and Ledwich *et al*. [5] summarised information on the results of various experiments and the activation energies and reaction orders calculated and noted that the activation energies are quite variable, being dependent on the catalyst and operating temperature. No firm agreement has been reached concerning the kinetic mechanism of methane catalytic oxidation. They indicated that platinum and palladium are generally accepted as the most active catalysts for low temperature total oxidation. Other catalysts have been tested but are less active. Lee *et al*. [2] pointed out that although the experiments were conducted at various conditions, it is clear that Pd/Al_2O_3 is by far the best, with Pt/Al_2O_3 the next most active.

3 ANCILLARY USES OF VENTILATION AIR METHANE

Ancillary uses involve substituting the ventilation air for ambient air in combustion processes. This has the advantage that methane in the ventilation air acts as a supplementary fuel in the combustion processes. As classified in Table 1, processes that can utilise ventilation air in this manner include:

- Pulverised coal-fired power stations,
- Hybrid waste coal/methane combustion units,
- Gas turbines, and
- Internal combustion engines.

Table 2 compares technologies for the ventilation air methane ancillary uses with aspects to main operational parameters, combustion organisation, technical feasibility and engineering applicability. Generally, energy recovery may be unquestionable for these technologies. However, the safety of connecting these units to mine shafts has not been fully examined and demonstrated.

3.1 PULVERISED COAL-FIRED POWER STATIONS

If ventilation air could be delivered to a large fuel consumer such as a coal-fired power station boiler, it could readily replace ambient air for all or part of the combustion air requirements. In Australia, a pilot-scale study has been carried out at the Vales Point Power Station to determine its feasibility. It has been reported that this technique is technically feasible, especially if the plant already exists or will soon be built near a mine ventilation shaft [6]. A full-scale demonstration of this technique at this power station is being planned with the support of the GGAP program to determine its feasibility at full-scale implementation [7]. The ventilation air will be fed at a rate of approximately 220m^3/s into the intake of the power station. The intake for the 2 × 660 MW pulverised coal fired boilers at Vales Point is approximately 1200 m^3/s.

Table 2 Differences of ventilation air methane ancillary use technologies*

Technology	Feature	Comb. temp.	Technical feasibility and engineering applicability	Potential issues
Pulverised coal-fired power station	Pulverised coal-fired furnace	1400~ 1650°C [8]	Tech: yes Eng: not demonstrated	- Limited sites - Potential operational problems to existing boilers
Hybrid waste coal/tailings /methane in a rotating kiln	Rotating kiln	1200~ 1550°C	Tech: not sure Eng: not demonstrated	- Self-sustaining combustion - Minimum requirement for waste coal/tailings quality
Hybrid waste coal/tailings /methane in a fluidised bed	Fluidised bed	850~ 950°C [9]	Tech: yes Eng: not demonstrated	- Minimum requirement for waste coal/tailings quality - Proving test needed for CH_4 oxidation
Conventional gas turbines	Gas turbine	1400~ 1650°C [10]	Tech: maybe Eng: not demonstrated	- Small percentage of turbine fuel - A lot of CH_4 emitted via by-passing air if no other compressor. But if so, increasing system complexity, and decreasing capacity of using ventilation air
Internal combustion engines	Engine	1800~ 2000°C [11]	Tech: yes Eng: demonstrated	- Small percentage of engine fuel - Using a small percentage of ventilation air

*Tech – technical feasibility; Eng – engineering applicability

In general, the lack of availability of power stations convenient to mines limits the suitability of this technique. Technically, for existing pulverised coal-fired power stations variations of methane in ventilation air might affect a stable operation of the conventional power station boiler furnaces depending on the methane concentration in air and the flow rate of ventilation air. This also increases the complexity of power station operation, which needs to be proved in terms of power station efficiency, power station and mine safety. It is possible that a quick increase the methane concentration in combustion air from 0% to 0.8% could result in flame instability leading to explosion or damaging the boiler due to possible overhigh combustion temperature, slagging and fouling if not controlled properly.

3.2 HYBRID WASTE COAL/TAILINGS/METHANE COMBUSTION UNITS

Regarding the methane oxidation mechanism and the way to replace combustion air using ventilation air, hybrid waste coal/tailings/methane combustion in a rotating kiln and a fluidised bed is similar to the pulverised coal combustion in boiler furnaces. However, principles of organising and stabilising the combustion are different.

3.2.1 Rotating kiln

CSIRO Exploration and Mining intends to develop a coal mine waste methane/coal utilisation technology, which promises not only to mitigate mine methane and utilise waste coal, but also to recover waste energy for power generation. It is expected that waste coal could be combusted with mine methane from both drainage gas and ventilation air inside a rotating kiln, in particular, drainage gas flame should play an essential role in stabilising combustion process inside the kiln. At present, a number of operating parameters of the combustion process need to be further investigated and determined for potential large-scale implementation. Some combustion runs have been conducted in a $1.2MW_t$ rotating kiln. Preliminary results suggest that the combustion performance of waste coal needs to be tested systematically to determine feasibility of waste coal combustion process inside the rotating kiln, and if so, to obtain the optimum operating parameters. It seems to be difficult to sustain the combustion without a pilot flame burning drainage gas of a different high quality fuel.

In early 1990s, Cobb [12] has examined the combustion performance of waste coals in a rotary kiln. The test results were disappointing, and showed that it was difficult to maintain sustained combustion even when large quantities of supplemental fuel were used. Combustion efficiency was poor, around 60 percent. The rotary kiln is ill-suited with respect to low-grade, hard to burn solid fuels, such as anthracite culm. Indeed, data from combustion of bituminous coal in the kiln unit suggest that with respect to coal in general, the rotary kiln boiler appears inferior to the circulating fluid bed boiler. The rotary kiln has an "open structure" which earmarks it for mass burn applications involving bulky and "gooey" fuels and wastes.

3.2.2 Fluidised bed

Fluidized beds suspend solid fuels on upward-blowing jets of air during the combustion process. The result is a turbulent mixing of gas and solids. The tumbling action, much like a bubbling fluid, provides more effective chemical reactions and heat transfer. The technology burns fuel at temperatures of 800 to 950^oC, well below the threshold where nitrogen oxides form (at approximately 1350^oC, the nitrogen and oxygen atoms in the combustion air combine to form nitrogen oxide pollutants). The mixing action of the fluidized bed results brings the flue gases into contact with a sulfur-absorbing chemical, such as limestone or dolomite. More than 95 percent of the sulfur pollutants in coal can be captured inside the boiler by the sorbent. Circulating fluidized-bed technology has the potential to improve operational characteristics by using higher air flows to entrain and move the bed material, and recirculating nearly all the bed material with adjacent high-volume, hot cyclone separators. The relatively clean flue gas flows to the heat exchanger. This approach theoretically simplifies feed design, extends the contact between sorbent and flue gas, reduces likelihood of heat exchanger tube erosion, and improves SO_2 capture and combustion efficiency [9]. There are about 14 CFBC power plants in Pennsylvania burning waste coals including anthracite culm. These power plants successfully demonstrated the advanced CFBC technology, which can directly fire unprocessed waste coal of ash content from 50% to 70% by weight that corresponds to a heating value of 7MJ/kg (minimum requirement for stable boiler operation) [13].

However, with regard to the hybrid waste coal/methane fluidised bed combustion, there is no experimental study yet that proves the methane can be fully oxidised in a fluidised bed combustion unit even the full oxidation is expected. It is recommended that test of this hybrid waste coal/methane fluidised bed combustion should be carried out before the development of a larger-scale unit.

3.3 INTERNAL COMBUSTION ENGINES

Internal combustion engines commonly use medium-quality gas to generate electricity, are good candidates for beneficially using part of a ventilation air stream by substituting it for fresh ambient air in the combustion air intake. As indicated in Table 2, it may emit more NO_x compared to other technologies due to the higher combustion temperature.

At the Appin Colliery, 54 one-megawatt Caterpillar 3516 spark-fired engines are installed, which use drainage gas as the primary fuel. The operation of these engines has demonstrated that methane from ventilation air only contributes between 4 and 10 percentage of engine fuel, corresponding to the consumption on the order of 20% ventilation emissions [6]. In fact, the engines do not currently use any ventilation air. Generally speaking, only a small percentage of methane from ventilation air can be used by this technology.

3.4 CONVENTIONAL GAS TURBINES

Similar to the gas engines, the methane from ventilation air only contributes a small percentage of turbine's fuel. Moreover, the use of this air for combustion dilution and cooling of the turbine inlet scroll and first stage in normal industrial gas turbines will result in a significant fraction of the methane passing through the turbine without combusting. This results in a more complex turbine system that requires compressed air from other sources, as well as compressed ventilation air, if all methane is to be combusted [14, 15, 16]. If a customer were to use mine ventilation air with a Solar turbine, the company would insist that the mixture's methane concentration remain below 0.5% to maintain the unit's cooling system. A richer mixture might support combustion and cause a dangerous temperature rise in the interior of the rotor [16].

4 PRINCIPAL USES OF VENTILATION AIR METHANE

Principal uses involve combustion of the methane in ventilation air as a primary fuel. As classified in Table 1, these technologies include:

- TFRR (VOCSIDIZER, MEGTEC)
- CFRR (CANMET)
- Catalytic monolith reactor (CSIRO)
- Catalytic lean-burn gas turbine (CSIRO, Ingersol-Rand)
- Recuperative lean-burn gas turbine (EDL)

- Concentrator (ECC)

It should be pointed out that the definition of “primary fuel” is not exact for some technologies depending on the CH_4 concentration in air and the minimum CH_4 concentration for the operational requirement, particularly where a lot of supplementary high quality fuel is required when recovering energy to generate power.

4.1 TFRR, CFRR AND CMR TECHNOLOGIES

Principles of the TFRR and CFRR technologies have been already described elsewhere [6, 16, 17]. Both TFRR and CFRR employ the flow-reversal principle to transfer methane’s heat of combustion, first to a solid medium, and then back to incoming air to raise its temperature to the ignition temperature of methane. The two systems differ only with respect to the use of a catalyst [6]. CMR technology is a honeycomb type monolithic reactor which is often used, and is known for its outstanding characteristics of very low pressure drop at high mass flows, high geometrical area, and high mechanical strength [18]. Monoliths consist of a structure of parallel channels with walls coated by a porous support containing catalytically active particles. Therefore, compared with the TFRR and CFRR units, the CMR unit should be more compact in terms of processing same amount of ventilation air, however a recuperator is needed to pre-heat the ventilation air to required temperature instead of the regenerative beds of the TFRR and CFRR units. Table 3 summarises the features of the TFRR, CFRR and CMR technologies.

4.1.1 Minimum methane concentration

As pointed out above, the volume of ventilation air is very large and the methane concentration is low and variable. This could cause some serious operating problems by using the TFRR and CFRR technologies in terms of continuous operation and recovering heat to generate electricity. For example, though MEGTEC has stated that the TFRR unit can continue to function at concentrations of 0.08% methane, the simulation results by The University of Utah indicated that blow-out would occur when methane concentration is below 0.35%. This goes counter to the MEGTEC statement [6]. Danell et al. [17] carried out trials in a pilot-scale TFRR unit attached to the ventilation air shaft of Appin Colliery, and reported that the unit can be operated on CH_4 concentration as low as 0.19%, however, they did not report how long the continuous operation lasted at such concentration. Indeed it is a practical issue in terms of mine-site operation due to that CH_4 in ventilation air could be lower than 0.19% from a few hours to a few weeks. Recent communication with the CONSOL Energy indicated that the minimum CH_4 concentration guaranteed by MEGTEC for continuous operation is 0.2% [19]. It is quite interesting to notice that two full-scale demonstration units processing $28m^3/s$ will be installed to a bleeding shaft of a mine in Pennsylvania which contains CH_4 from 0.9% to 1.5% due to the concern of risk of continuous operation [19]. Also, it has been indicated that over 200 operators of the TFRR units regularly add natural gas to the industrial airflows to maintain combustion [6].

To sustain the CFRR operation the minimum methane in the ventilation should be above 0.1% [6]. A question similar to that being asked for the TFRR is how long the CFFR unit can be operated with 0.1% CH_4 in air. According to the experimental catalytic combustion results obtained in a CMR laboratory-scale rig, the CMR can be continuously operated when CH_4 concentration is not less than 0.4% and the air is preheated up to 500^oC by a recuperator using flue gas from the CMR [14, 15].

Table 3 Comparison of the technologies

Feature	**MEGTEC TFRR**	**CANMET CFRR**	**CSIRO CMR**
Principles of operation	Flow reversal	Same as TFRR	Monolith reactor
Catalyst	No	Yes	Yes
Auto-ignition temperature	1000^oC	$350\sim800^oC$	500^oC
Experience	600+ units in field, some operating on methane	Bench-scale trials with simulated mine exhaust	Bench-scale study on combustion
Cycle period length	Shorter	Longer	Continuously
Minimum CH_4 concentration	0.2%	0.1%	0.4%
Applicability	CH_4 mitigation	CH_4 mitigation	CH_4 mitigation
Possibility of recovering heat to generate power	Need additional fuel to increase CH_4 concentration and maintain it constant	Need additional fuel to increase CH_4 concentration and maintain it constant	Need additional fuel to increase CH_4 concentration and maintain it constant
Variability of CH_4 concentration	Variable	Variable	Variable
Plant size	Huge	Larger	Compact
Operation	More complicated	More complicated	Simple
Lifetime	N/A	N/A	>8,000 hours for catalysts,
NO_x emission	Higher	Low	Low (<1ppm)
CO emission	Low	Low	Low (~0ppm)

4.1.2 Technical feasibility and applicability

Some of the mine sites have very low power rates, do not have a need for any additional power, or have at best only intermittent power needs. Therefore, these mines are interested in investigating means of destroying ventilation air methane other than in power-generation applications. There could be no doubt that the TFRR, CFRR and CMR technologies are technically feasible for this purpose when the CH_4 concentration in air exceeds the minimum requirement by each technology and economic performance is not critical.

With the respect of engineering applicability, these technologies can be used to destroy methane in ventilation air as methane mitigation technologies. However, for some mine sites the continuous operation of these units may need additional fuel depending on the CH_4 concentration being not less than the minimum requirement or how long the operation can last at the minimum CH_4 concentration. It is very interesting to notice the size of the two TFFR units driven by a fan that CONSOL Energy will install at a mine site to process $28m^3/s$ ventilation air. The dimensions of the units are 14.62m long, 11.79m wide and 4.49m high. So, to process all of ventilation air from a typical mine, the site for TFFR units is at least 63m×14.62m×4.49m for 150m^3/s, and 126m×14.62m×4.49m for 300m^3/s assuming the units are placed in a line. It is estimated based on the experimental data that one eighth of this area is required by the CMR to process the same amount of ventilation air.

In addition, the TFRR and CFRR can handle variability of methane concentration in ventilation air due to the thermal inertia of the systems, so does the CMR with a recuperator when CH_4 concentration not less than 0.4%.

4.1.3 Heat recovery

If the methane concentration is almost constant, recovery of heat released by methane combustion can be used to generate power. If the methane concentration in the ventilation air is variable, it is difficult to extract useful energy as the variations in methane concentration are likely to cause instability in the system, as it is difficult to maintain the working fluid that recovers the heat at a constant temperature and flow rate. It is rare for ventilation air from mines to contain even approximately constant methane, and it is common for it to fluctuate greatly with changing mine operations.

It should be possible to recover surplus heat from the systems when they are operating with methane concentrations above the minimum. This needs to be transferred into a working fluid, such as hot water/steam for a steam turbine or air for a gas turbine. Some of the heat is required to maintain reactor temperature, and if methane concentrations are in the lowest sustainable range, most or all of the heat of combustion goes for maintaining the reactor temperature. However, this heat recovery process depends on whether the methane concentration in the ventilation air is almost constant or not. When the methane concentration is variable, it is difficult to use normal heat exchangers (steam or hot air production) to cope with the reactor temperature variations. This has been demonstrated by the experimental results obtained by Danell et al. [17] in the pilot-scale TFFR unit. The heat absorbed by cooling water is very sensitive to the methane concentration in air. Figure 2 is an example that shows this sensitive relationship. This is because the heat flux from the combustion side to the cooling water is almost dependant on the temperature approach that is determined by CH_4 concentration in air rather than heat transfer area and heat transfer coefficient that are almost constant once the heat exchanger is installed into the bed.

Assuming that a suitable heat exchanger could be designed, the temperature fluctuations in the steam or air being produced would result in instability in the operation of the attached turbine. Therefore, in order to recover heat for power generation while retaining stable operation of the reactor and attached turbine, it is necessary to maintain constant methane concentrations in the feed air, typically requiring addition of natural gas. So, practically BHP Billiton plans to install a TFRR system combined with a conventional steam turbine. The unit will use drainage gas from the mine to even out fluctuations in the ventilation air in order to maintain the concentration entering the unit at 0.9%. The two large units will consume approximately 57.5 m^3/s of ventilation air [7]. In addition, as mentioned above, CONSOL Energy will evaluate the feasibility of power generation by recovering the heat from their demonstration units during planned future12 months continuous operation [19]. It is expected that the performance data from the future full-scale demonstration units from Australia and USA should proof this analysis, i.e. that the additional fuel is necessary for the power generation operation.

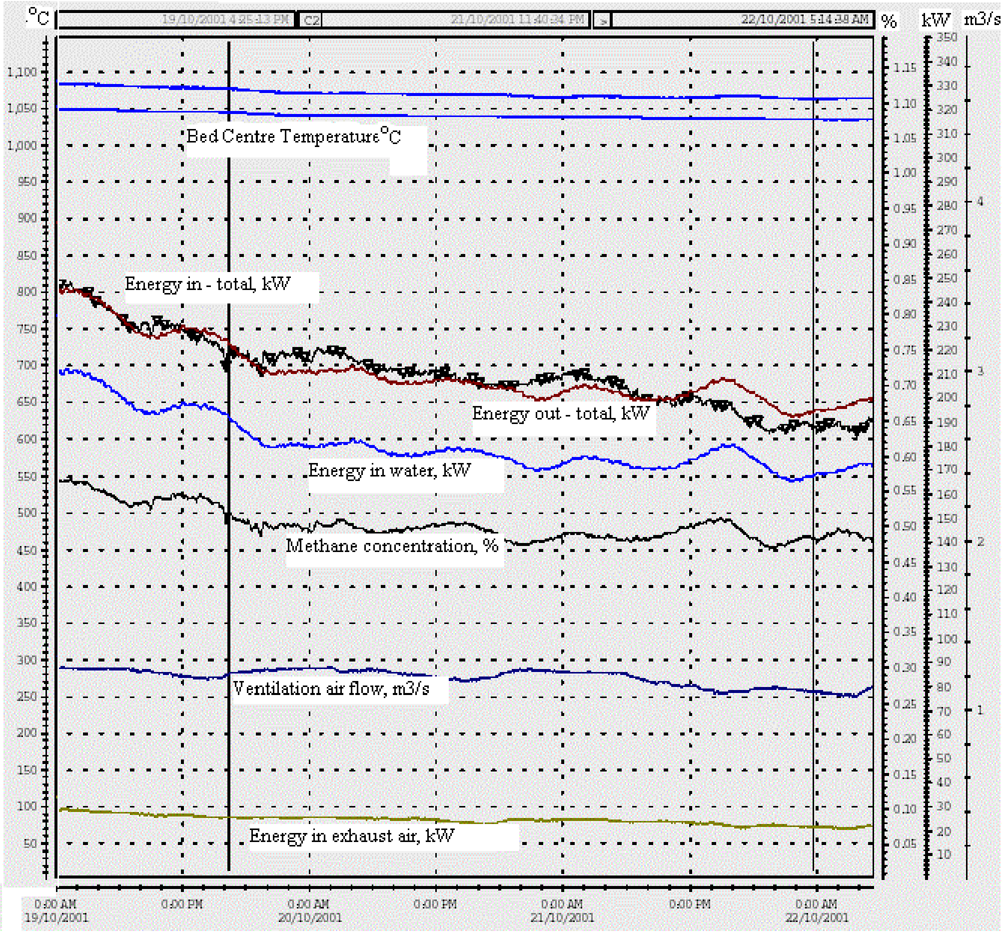

Figure 2 TFRR test unit operating chart
(Extracted from Ref. [17])

4.2 LEAN-BURN GAS TURBINES

There are several lean-burn gas turbines being developed in the world. These include EDL's recuperative gas turbine, CSIRO lean-burn catalytic turbine and Ingersol-Rand (IR)'s microturbine with a catalytic combustor [1]. Table 4 summarises the features of lean-burn gas turbines. EDL technology is a recuperative gas turbine, which uses heat from the combustion process to preheat the air containing methane to the auto-ignition temperature (in the range 700-1000°C), with the combusted gas being used to drive a turbine. Reportedly, this gas turbine can sustain the operation when the methane concentration in air is above 1.6%, which leads to the air being preheated to 700°C before combustion. It requires addition of substantial quantities of methane to the ventilation air to operate. Announced on 17 May 2001, EDL will receive $11 million to install and operate four 2.7MW$_e$ recuperative gas turbine generators at Anglo Coal's German Creek Mine in Central Queensland. The project is expected to achieve large-scale abatement much earlier than the 2008 deadline [7]. These gas turbines are modified Centaur unit from Solar Turbines. All the pre-drainage, post drainage and some ventilation air are ingested into the intake of the axial compressor at a pressure of approximately -10kPa. The mixture is preheated by a recuperator to 450°C. Then recuperative combustion chamber uses the hot combustion products to further heat the fuel-air mixture to a point where ignition occurs. The fuel and air mixture is injected through stainless steel tubes into combustion region. The burnt gas then passes up the outside of the stainless steel tubes to heat incoming air, and then enters into the turbine inlet to drive the turbine. This heat exchange reduces the exit temperature of air to 850°C, which is the same as the standard Centaur turbine. With this design, there is a need to use a turbine that has a low combustion temperature. This type of turbine has no bypass and no blade bleed cooling so that all the mine ventilation gas passed into the combustion chamber [20].

Table 4 Comparison of the technologies

Feature	**EDL Recuperative Turbine**	**CSIRO Catalytic Turbine**	**IR Catalytic Microturbine**
Principles of operation	Air heater inside combustion chamber	Monolith reactor	Monolith reactor
Catalyst	No	Yes	Yes
Auto-ignition temperature	700~1000^{o}C	500^{o}C	N/A
Experience	Pilot-scale trial	Bench-scale study on combustion	Conventional microturbine development
Cycle period length	Continuously	Continuously	Continuously
Minimum CH_4 concentration for operation	1.6%	1%	1%
Applicability	CH_4 mitigation and power generation and need additional fuel to increase CH_4 concentration	CH_4 mitigation and power generation and need additional fuel to increase CH_4 concentration	CH_4 mitigation and power generation and need additional fuel to increase CH_4 concentration
Possibility of recovering heat	Feasible (power generation)	Feasible (power generation)	Feasible (power generation)
Variability of CH_4 concentration	Constant	Constant	Constant
Operation	Simple and stable	Simple and stable	Simple and stable
Lifetime	May be shorter due to the high temperature combustion heat exchanger	>8,000 hours for catalysts, and 20years for a turbine.	N/A
NO_x emission	Higher	Low (<3ppm)	Low
CO emission	Low	Low (~0ppm)	Low

Reduction of the minimum methane concentration at which a turbine system can operate has substantial advantages in reducing usage of methane from other sources. So, Su et al. from CSIRO invented a 1% methane catalytic combustion gas turbine based on the CH_4 catalytic combustion experimental data and the design criteria of a turbine [14], which has been patented [21]. The 1% CH_4 turbine can use a much greater proportion of ventilation air compared with 1.6% CH_4 gas turbine. Following the 1% CH_4 turbine development in Australia, Ingersol-Rand in USA is also developing a microturbine with a catalytic combustor powered with 1% CH_4 in air. Thermodynamically, lean-burn catalytic turbines can be operated at lower methane concentrations, perhaps to 0.8% [1, 14]. In general, the catalytic turbine usees a very lean fuel/air mixture to the air intake, compresses it, and combusts it in a catalytic combustor. This turbine will not use combustion air for dilution and internal cooling, and thus allowing the air intake to contain fuel.

The technical and economic assessment has been carried out on the implementation of 1% and 1.6% methane gas turbines on the basis of real methane emission data from two Australian gassy coal mines, and also presented in detail in this conference [22]. The results indicated that 50 to 100% of the fuel for firing the 1% methane catalytic turbine is the methane from ventilation air, compared to only 30~60% for the 1.6% methane recuperative turbine, depending on the methane concentration in the ventilation air. Also, the 1% turbine can utilise about 100% of ventilation air for both mines, but the 1.6% turbine just uses 50% and 36% of ventilation air for the two mines respectively.

4.3 CONCENTRATOR

Concentrators have been applied to several industries to capture volatile organic compounds. So, a concentrator could be used to enrich methane in mine ventilation air to levels that meet the requirements of lean-burn methane utilisation technologies, such as catalytic and recuperative gas turbines. This involves taking the 0.1 to 0.9% methane stream and concentrating the methane to a concentration of 20%. If the methane can be concentrated to approximately 30% or higher, conventional gas turbines can be employed to generate electricity without significant modifications. In addition, the concentrator can also act as a buffer to cope with variations in methane concentration and methane flow rate.

Environmental C & C, Inc. (ECC) manufactures a fluid bed concentrator and is conducting tests on that system's efficiency using simulated ventilation air with 0.5% CH_4 [1], and selecting most efficient adsorbent medium for the process. CSIRO also proposes a research project that aims to develop a prototype laboratory concentrator with a capacity of processing $400m^3/h$ ventilation air with different methane concentrations. The concentrator consists of an adsorber, a storage vessel for the adsorbent medium with the adsorbed methane, a desorber and a transporting/feeding system for the adsorbent medium. The adsorber is a hybrid multistage fluidised/moving bed, consisting of a series of adsorbent medium fluidised beds. The ventilation air enters from the bottom of the adsorber, passing upward through the fluidised beds to enhance capture of methane. The adsorbed methane could make the adsorbent medium heavier, 7~20% on a weight basis, and it falls to the bottom of the adsorber, from where it is discharged to the storage vessel and then the desorber. The medium is regenerated by increasing the temperature, which results in the release of concentrated methane into a low volume stream. The adsorbent medium is then recycled back to the adsorber for reuse. Based on the literature study, it is recommended that activated carbon is the best candidate for the adsorbent for this process followed by zeolite. The activated carbon has a sorptive capacity of 0.4~0.7kg/kg (dry) depending on raw materials used for the carbon production. In conclusion, a successfully demonstrated unit (concentrator) would make a breakthrough of development of mine ventilation air methane utilisation technologies.

5 CONCLUSIONS

This paper reviews the existing and developing technologies of coalmine ventilation air methane (CH_4) mitigation and utilisation, particularly in the field of CH_4 oxidation, with the respects of their technical feasibility, engineering applicability, and possibility of recovering heat released from CH_4 oxidation.

Substituting ventilation air for ambient air in conventional pulverised coal power station boiler furnaces, and hybrid waste coal/methane rotating kiln/fluidised bed combustion units has the advantage that methane in the ventilation air acts as a supplementary fuel in the combustion processes, and also energy recovery may be unquestionable. However, the safety of connecting these combustion units to mine shafts has not been fully examined and determined, and the hybrid combustion technologies have to be successfully demonstrated before any further development of a larger scale unit. Internal combustion gas engines and conventional gas turbines only use a small part of ventilation air, which contributes 4-10% of engine/turbine's fuel. Moreover, the turbine system is more complicated due to the need for one more compressor.

There could be no doubt that the TFRR, CFRR and CMR technologies are technically feasible to mitigate ventilation air methane when the CH_4 concentration in air exceeds the minimum requirement and economic performance is not an issue. These technologies can cope with the variations of methane concentration and flow rate. However, for some mine sites the continuous operation of these units may need additional fuel depending on the CH_4 concentration being not less than the minimum requirement and how long the operation can last at the minimum CH_4 concentration. In addition, to recover heat from these units for power generation additional fuel is needed to increase methane concentration to a constant level, perhaps, at least 0.9% according to the current design practices.

At present, lean-burn gas turbines seem to be cost-effective technologies of mitigating and utilising ventilation air methane with additional methane from drainage gas. The 1% CH_4 turbine can use a much greater proportion of ventilation air compared with the 1.6% CH_4 gas turbine. Thermodynamically, lean-burn catalytic turbines can be operated at lower methane concentrations, perhaps to 0.8%. Then 50 to 100% of the fuel for firing the 1% methane catalytic turbine is the methane from ventilation air, compared to only 30~60% for the 1.6% methane recuperative turbine, depending on the CH_4 concentration in the ventilation air. Also, the 1% turbine can utilise about

100% of ventilation air for both mines, but the 1.6% turbine just uses 50% and 36% of ventilation air for the two mines respectively. Therefore, the 1% CH_4 catalytic turbine is the most prospective technology up to date, and in particular can be directly used for ventilation air of bleeding shaft containing 0.9-1.5% CH_4 without the need for additional fuel in most of gassy mines in the USA.

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