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Development and site trials of a novel pilot ventilation air methane catalytic mitigator

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Executive summary

In collaboration with South32 Illawarra Metallurgical Coal, CSIRO has undertaken a CINSW-funded project to develop and site-trial a novel pilot-scale catalytic flow-reversal reactor (CFRR) to directly abate ventilation air methane (VAM) emissions from NSW coal mines. The motivation to evaluate CFRR technology arises from the advantages CFRRs have compared to conventional regenerative thermal flow-reversal reactors (TFRRs). CFRRs can oxidise methane at much lower temperatures (350-600 °C compared to 850-1300 °C for TFRRs) and can process higher ventilation air (VA) flows with significantly lower methane concentrations. Lowering the operating temperature can avoid sintering and ceramic corrosion and benefit safety management. Handling high VA flow rates with dilute VAM leads to a small footprint of the mitigator unit and enables direct mitigation of low-level VAM.

CSIRO's pilot-scale catalytic VAM mitigator (VAMMIT) was developed by redesigning and retrofitting catalysts to the regenerative bed used in an existing pilot-scale thermal VAMMIT unit that was trialled at Appin coal mine (WestVAMP) earlier through a CMATSP project.

Specific objectives of this project which commenced in January 2019 were to:

- Design a novel VAM catalytic oxidation regenerative bed
- Modify and construct the regenerative bed of the existing VAMMIT unit at WestVAMP with catalysts and ceramic materials
- Commission and test functions of the catalytic VAMMIT prototype unit
- Demonstrate the performance of the catalytic VAMMIT prototype unit with diluted and undiluted mine-site VAM and determine optimum operational parameters.

Within the physical constraints of the thermal VAMMIT, the dimensions of the new regenerative bed were determined, based on previous laboratory catalyst performance tests and operational experience with the CSIRO ventilation air methane catalytic turbine (VAMCAT) catalytic combustor. The mass and energy balances of the catalytic VAMMIT were calculated to determine the heights of the ceramic blocks and catalytic layers with various operational conditions such as VA flow rates, VAM concentrations and flow switching time.

In the two decades since CSIRO developed the VAMCAT, alumina supported palladium (Pd/Al_2O_3) catalysts loaded onto honeycomb monolithic ceramic blocks by washcoating have remained the most active catalyst for methane oxidation. Eight honeycomb monolith Pd/Al_2O_3 catalysts were tested at CSIRO laboratories under various reaction conditions such as methane concentrations, preheated air temperatures and space velocities. The best one was found to result in over 99% of methane conversion at a relatively low temperature range of 300-350 °C within a range of required space velocities. Due to the improved performance of the tested catalysts, the catalytic VAMMIT bed design was recalculated using a preheated air temperature of 350 °C. As a result, this led to a significant reduction in the operational temperature of the catalytic VAMMIT, which is much lower than the temperature originally targeted in the project proposal (450-750 °C), representing a significant improvement.

As the previous snorkels over the mine VA shafts at WestVAMP installed to extract and pipe VA for testing had been removed by the mine site, two new snorkels were designed by the project team and installed for site trials of the catalytic VAMMIT. Site construction, including construction of the new regenerative beds and installation of control and safety systems was completed by the end of 2019. However, due to the impact of the pandemic and associated travel restrictions, the commissioning and site trials were significantly delayed.

The catalytic VAMMIT unit was tested for 476 hours in total using several combinations of VAM concentrations (0.08-0.38 vol%) and VA flow rates (0.33, 0.5 and 0.67 Nm^3/s) to evaluate its performance. It was demonstrated that the catalytic VAMMIT reaction can be self-sustaining with low VAM concentrations of 0.1-0.13 vol% and at VA flow rates of 0.5 to 0.67 Nm^3/s. The efficiency of methane oxidation was in the range of 84-90%. The catalytic bed temperature can be maintained in the range of 440-550 °C, which is much lower than that of TFRRs above 1000 °C.

It was, however, challenging for the current catalytic VAMMIT prototype unit to process more than 0.3 vol% VAM. It was found that the excessive reaction heat generated from the oxidation of high-concentration VAM was not effectively removed from the regenerative bed of the current prototype unit. Although the average temperature of the catalytic layers was less than 650 °C, when operating with over 0.3 vol% VAM, some hot spots (> 800 °C) in the catalytic bed were observed. Such uneven temperature distributions within catalytic layers inside the bed could result in lower methane oxidation efficiencies than those obtained with the laboratory tests.

Nonetheless, during the entire testing period, catalyst performance was found to be stable even when the inlet VA flow rate was increased to 0.67 Nm^3/s, the maximum capacity of the blower. To further understand the impact of VA flow rate on catalyst performance, through consultation with CINSW, a new blower with a nominal capacity of 2 Nm^3/s was installed, which was outside the initial project scope of work. Results of trials with the new blower are not included in this report but will be presented in a supplementary report.

The regenerative bed was thoroughly inspected after the completion of all the trials including testing with the new blower. It was found that almost all the catalytic and ceramic blocks remained in good condition with only a few cracked and broken among over 1000 blocks. It is highly likely that such a small number of blocks were damaged during the bed installation. It indicates that the bed materials are mechanically stable and can tolerate thermal cycles associated with catalytic VAMMIT. In addition, major leakages of mechanical parts that direct the VA flow through the catalytic bed were found in the bed inspection, which would cause part of VA flow bypassing the catalytic bed and being released into the exhaust without oxidation. It partially contributed to the measured low VAM oxidation efficiency below 90% in site trials.

A preliminary life cycle assessment (LCA) was carried out to study the net reduction of greenhouse gas emissions that can be achieved by implementing a full-scale catalytic VAMMIT that can treat 17 Nm^3/s of VA. Three components of CO_2-e emission were considered in the LCA, including (1) CO_2 in the feed VA, (2) unreacted methane in the flue gas released from the catalytic VAMMIT, and (3) CO_2 in the flue gas generated from methane oxidation. Three scenarios (i.e., no VA treatment, 90% and 95% methane oxidation efficiencies) were investigated. Compared to the case of no VAM mitigation, when processing 0.1 vol% VAM, the reductions of CO_2 emissions were 63.8 and 67.6% for 90 and 95% methane conversion, respectively. The higher the VAM concentration is, the more significant CO_2 emissions reductions the catalytic VAMMIT can achieve. For example, 90% methane conversion can yield 74.9, 77.4 and 78.8% CO_2-e reductions when treating 0.3, 0.5 and 0.8 vol% VAM, respectively.

Apart from also possessing thermal VAMMIT advantages in terms of low pressure drop and compact footprint, the new catalytic VAMMIT has demonstrated additional advantages evidenced by the results of site trials: (1) enhanced VA processing capacity, capable of treating high VA flows, (2) lowered operational temperatures to below 500 °C to completely avoid sintering and ceramic corrosion with stone dust, (3) enhanced safety management due to lower operating temperature and less heat accumulated in the bed, and (4) self-sustaining operation with reduced minimum methane concentration around 0.1 vol%. The self-sustaining operation at low operation temperatures and methane concentrations, enabled by catalytic VAMMIT is particularly important for VAM abatement in Australia.

The concentration of methane in the VA from exhaust shaft at Australian coal mines has increasingly declined as mining operations continue, and typically concentrations fluctuate in the range of 0.2-0.4 vol%. Existing thermal mitigators cannot effectively oxidise VAM below 0.3 vol%. There is an urgent need to accelerate the development of catalytic VAMMIT as a highly capable and practical technology solution for directly abating such dilute VAM emissions in a cost-effective manner. This was the first catalytic VAMMIT prototype and its design was constrained by the dimensions and layout of a previous TFRR in which it was retrofitted. Based on the findings of the development and trials of the current 1st prototype pilot unit, the regenerative bed structure and control system will be redesign and optimised as part of the next stage of catalytic VAMMIT development.

Lay Summary

This report describes the design, development and pilot-scale field trials of a novel system to convert the methane contained in the ventilation air exhaust (VAM) of underground coal mines to carbon dioxide by a process of catalytic oxidation. Because VAM can contribute up to 15% of Australia's annual methane emissions, replacement of methane by carbon dioxide can produce a significant positive response to Australia's greenhouse gas reduction commitments noting that carbon dioxide's 100-year global warming potential (GWP) is only 4% of that of methane.

VAM conversion is currently achieved on a commercial basis by thermal oxidation which is an extremely high temperature process (~1000 °C). These systems have high maintenance requirements and possess safety concerns to mine site implementation due to high temperature operation. Moreover, they cannot effectively process very dilute VAM streams, which is a requirement in Australian conditions. Catalytic systems operate at lower temperatures and higher flow rates at lower VAM concentrations, and require less input power, so have the potential to be an attractive alternative to thermal oxidation systems. In response to this opportunity, CSIRO has evaluated potential catalysts and has developed a new reactor with a bed structure comprised of high-performing catalytic materials on a monolithic ceramic substrate through which the VAM is passed and converted into carbon dioxide. The reactor is designed based on the flow-reversal concept, consisting of two gas flow modes, i.e. forward and reverse flow, which cycle to enable VAM preheating and oxidation in a self-sustaining manner without additional heat input.

A pilot-scale system comprising a catalytic reactor and pipework to deliver actual ventilation air for the trials was built and installed at Appin mine. An extensive control and monitoring system was also developed which incorporated a number of safety systems to comply with mandated mine requirements.

Eleven individual tests with a range of VAM concentrations and ventilation air flow rates were conducted over a total of 476 operating hours to establish operating limits and system performance. It was found that the methane oxidation efficiency varied between 84 and 90%. While this is lower than is currently achieved in thermal systems, reasons for this efficiency reduction have been identified. Importantly, the operating limits established, such as flow rate, minimum VAM concentration, and operating temperature range confirmed the predicted advantages over thermal systems.

Because catalytic methane conversion offers significant benefits, the report recommends that further development of catalytic oxidation is carried out including extended prototype field trials to identify longer-term issues, optimisation of the conversion bed design including improved heat management, and investigation of cost-effective catalytic materials which would be necessary for commercial-scale implementation.

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List of abbreviations

Abbreviation	Definition
CFRR	Catalytic flow-reversal reactor
CINSW	Coal Innovation NSW
CMATSP	Coal mining abatement technology support package
DP	Differential pressure
GC	Gas chromatography
GWP	Global warming potential
HAZOP	Hazard and operability analysis
HMI	Human machine interface
IMC	Illawarra Metallurgical Coal
LCA	Life cycle assessment
LCI	Life cycle inventory
LPG	Liquified petroleum gas
MFC	Mass flow controller
NATA	National Association of Testing Authorities
P&ID	Piping and instrumentation diagram
RPM	Revolutions per minute
SI	Site infrastructure
TFRR	Thermal flow-reversal reactor
VA	Ventilation air
VAM	Ventilation air methane
VAMCAP	Ventilation air methane capture
VAMCAT	Ventilation air methane catalytic combustion gas turbine
VAMMIT	Ventilation air methane mitigator
VSD	Variable speed drive

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Finally, the team would like to convey its heartfelt gratitude to Dr Shi Su, the original project leader and proponent of this technology, for his impressive legacy in leading and achieving world-class research and development in the field of emissions abatement over several decades.

1 INTRODUCTION

1.1 Background

According to the International Energy Agency (IEA) (IEA 2023), coal mine methane emissions in Australia are continuing to grow, currently accounting for 30% of Australia's annual methane emissions. Furthermore, 50-85% of these emissions, depending on the mine site, occur via mine ventilation air (VA) (Moreby et al. 2010). Other researchers estimate that ventilation air methane (VAM) contributes 60-70% of all underground coal mining methane emissions (Karakurt et al. 2011; Zhu et al. 2017). To respond to Australia's climate commitments, including greenhouse gas emissions reduction by 43% below 2005 levels by 2030, net zero emissions by 2050 and the Global Methane Pledge (30% methane emissions reduction below 2020 levels by 2030), the coal mining industry in Australia faces the need to reduce VAM methane content via mitigation or use of VAM as an energy source. However, due to the intrinsic nature of VA, such as large and variable flow rates (120-600 m^3/s for typical Australian gassy mines), very dilute methane concentrations (< 1 vol%), high relative humidity (70-100%) and the presence of dust particles (Su et al. 2008), it has been a great challenge for the coal mine industry to abate VAM.

To tackle this prolonged challenge, considerable work has focused on the oxidation of VAM as a primary fuel in low concentration processes by converting methane to carbon dioxide through either thermal or catalytic oxidation (Yin et al. 2020). Su et al. (2020) in a recent review of the global status of VAM abatement technology development identified that previous research had concentrated on developing technologies for VAM abatement through thermal oxidation at 850-1300 °C. Substantial engineering and operational experience has been gained by various technology vendors through site trials and demonstrations of industrial-scale thermal flow-reversal reactors (TFRRs), which are based on thermal oxidation processes that operate above 1000 ^{o}C. It is noted that as of today, TFRR is the only technology that has been site trialled and demonstrated with actual VAM at commercial scale. Existing TFRRs equipped with a packed bed structure suffer from two major operational issues: (1) dust deposition/clogging inside the bed resulting in frequent unit shutdowns and high maintenance costs and (2) high pressure drop through the packed bed leading to high power consumption during operation.

To resolve these issues, CSIRO has developed a new VAM mitigator (VAMMIT) (Su et al. 2013; Yin et al. 2020) where the packed bed in a conventional TFFR is replaced by a novel honeycomb monolith bed structure which significantly reduces the pressure drop and avoids dust deposition and sintering inside the bed. This can considerably reduce the operational and maintenance costs such as power consumption, regenerative bed cleaning and shutdown time due to the elimination of dust deposition inside the bed. This bed also incorporates an innovative flow diverting section located at the bed centre with connections to a gas burner for easy start-up and a burst disc for safety management. VAMMIT technology has been developed at pilot scale and has successfully operated at a CSIRO site and recently at the Appin coal mine (the WestVAMP plant) using actual VAM in the concentration range of 0.3-1 vol% for two months, on a 24/5 test campaign schedule in a CMATSP project. Importantly, no dust deposition was observed during the two-month site demonstration.

1.2 Catalytic flow reversal reactors (CFRRs)

This project utilises a new approach to large-scale VAM mitigation, the catalytic flow reversal reactor (CFRR). Because CFRRs have not been used previously at the required scale, there is a lack of technical information, particularly experimental data. The earliest CFRR used exclusively for VAM treatment may be the CH4MIN technology that was conceived and developed by Canada's CANMET Energy and Technology Centre in 1995 (Hristo and Gilles 2003). CFRRs are still at an early stage of development, including one commercial-scale test unit at a Chinese coal mine that was not commissioned, and a pilot-scale prototype unit being developed through this project by CSIRO.

The catalytic VAMMIT to be described also employs the CSIRO-developed honeycomb monolith structured bed, which is different to the commercial-scale CFRR test unit which used a conventional packed bed. It has the following additional main advantages over current thermal oxidation-based systems:

1. Smaller footprint: the catalytic unit is able to process a much higher VA flow, leading to greater space velocity (air flow rate/reactor bed volume) of 15,000 hour^{-1} (h^{-1}) than that (1,000-2,000 h^{-1}) achieved in a thermal oxidation unit.
2. Lower operational temperatures: the operational temperature is in a range of 350-650 °C which is below the stone dust ($CaCO_3$) decomposition temperature of 900-1050 °C, completely avoiding sintering and ceramic corrosion with CaO.
3. Enhanced safety management due to lowered operational temperature.
4. Operation in lower methane concentrations: Self-sustaining operation in a minimum methane concentration of less than 0.3% that cannot be treated by a TFRR.

The commercially available catalysts required for CFRR are usually based on noble metals (e.g., Pd, Pt etc), which are very expensive. The honeycomb monolith catalysts used in the catalytic VAMMIT prototype unit are Pd based. Alumina-supported Pd catalysts are loaded onto honeycomb-shaped ceramic blocks by a washcoating technology which is the most popular coating technique for catalyst fabrication and is currently applied at industrial scale for ceramic (cordierite) and metallic (Fecralloy) automotive exhaust cleaning monoliths (Pennemann et al. 2013). Our laboratory tests indicated that high-loaded catalysts have an excellent resistance to moisture above 350 °C, which needs to be confirmed through long-term operation with actual VA.

The commercial potential of CFRR implementation at mine sites will depend on the capital cost (as a function of the ventilation air flow rate), maintenance costs and safety benefits compared with TFRR.

1.3 Scope of work

This project aimed to develop a novel, catalytic mitigator to directly abate VAM emissions from NSW coal mines. A novel, pilot-scale, VAM catalytic oxidation prototype unit was developed with two sections of catalysts inside a refractory bed. The existing thermal VAMMIT unit at WestVAMP was modified with a custom-built, catalytic oxidation regenerative bed. The unit was commissioned and trialled with actual VAM at the mine site to demonstrate its performance. The specific objectives of this project were to:

- Design a novel VAM catalytic oxidation regenerative bed.
- Modify the existing VAMMIT unit at WestVAMP with catalysts and ceramic regenerative bed materials.
- Commission and test functions of the catalytic prototype unit.
- Demonstrate the performance of the catalytic prototype unit with diluted and undiluted mine-site VAM and determine optimum operational parameters.

1.4 Project work program

Although the project was significantly delayed by COVID-19 and other impacts, the project team was able to complete all planned mine site hot trial tests. The catalytic VAMMIT unit was tested for 476 hours in total under various VAM concentrations of 0.08-0.38 vol% and three VA flow rates (0.33, 0.5 and 0.67 Nm^3/s). During the testing period, the unit was fully functional, and the catalyst performance was stable. No significant degradation was observed. In addition, after the approval of CINSW, a new blower with higher capacity (nominal 2 Nm^3/s) and associated piping were installed to further investigate the performance of the catalytic VAMMIT unit. As discussed in Chapter 5, the test results obtained after modifications to the unit are not included in this report but will be presented separately in a supplementary report. Table 1 summarises the timeframe and achievement of each milestone.

Table 1 Summary of project milestones

Milestones	Timeframe		Performance Measure	
	Start date	Completion date	Specify how the results (outcomes/outputs) will be measured	Status and Relevance to project and achievement
M1: Project establishment, and design calculations	1/1/2019	31/3/2019	The project registered at Appin coal mine Completion of design calculation	Completed • The project was formally registered at Appin coal mine in March 2019 by extending the collaborative research agreement between CSIRO and South 32 to the end of 2020 (this was further extended to 30 June 2022 to reflect the delays caused by COVID-19), revising the project execution plan (PEP) and small project safety management plan (NSW) (SMP) • Design calculations for the catalytic regenerative bed were completed based on the thermal version VAMMIT experimental data and catalyst performance tested in 2001-02 and for the VAMCAT experiments. The design was later revisited and finalised in June 2019 based on the latest test results of eight commercial Pd-based catalysts and the moisture effects
M2: Design of the catalytic refractory bed, and procurement of materials	1/4/2019	30/6/2019	Completion of the design and procurement including - Detailed drawings of the regenerative bed with the catalyst layers, - Materials including custom-made catalysts procured	Completed • Intensive catalyst performance tests were completed, and promising test results were obtained, showing that completed methane oxidation can be achieved at temperatures as low as 300-350 ^{o}C and no moisture effects were observed under certain experimental conditions • Detailed engineering design and 2D/3D drawings of the catalytic regenerative bed were completed • Materials including catalysts, insulation materials, honeycomb monolith ceramics, thermocouples, etc. were procured • In addition, extra tasks out of the original scope including start-up burner tests for low-temperature pre-heating and engineering design for a small snorkel to connect the catalytic VAMMIT unit with the mine shafts (the previous larger snorkel was removed by the mine for safety reasons) To meet mine site regulations, the mechanical design of the snorkel and catalytic bed was verified by a third party, with no non-compliance items found
M3: Fabrication of CSIRO-developed	1/7/2019	30/9/2019	Ceramic blocks fabricated and the completion of plant dossier	Completed • Ceramic blocks specifically designed for the flow diverting section were fabricated in the lab

ceramic blocks, and plant dossier				• A safety plant dossier composing of technical specifications of all parts and components, material safety datasheets, operational documents such as commissioning and operational procedures was compiled and submitted to mine site
M4: Unit modification	1/10/2019	31/12/2019	Completion of the unit modification	Completed • The catalytic bed was installed by modifying the previous thermal version regenerative bed and replacing part of thermocouples • The snorkel piping was installed
M5: Commissioning and function tests	1/1/2020	16/6/2021	Completion of commissioning and functional tests - Each component in the unit: mechanical, electrical - Instrument - Start-up burner ignition	Completed Due to the extended power outrage at the mine site (January-March 2020), travel restrictions caused by COVID-19 (March-December 2020) and approval process (January-May 2021), this milestone was delayed by almost 17 months. When the project team returned to site on 10th June 2021, this milestone was completed: • Functional tests of all parts and components were carried out, no malfunction found • Trip-related sensors and instrument were calibrated by a third party • Start-up burner ignition trials were successfully performed with LPG and fresh air
Stage Gate Report	01/05/2021	16/06/2021	Completion of stage gate reports: - Project milestones up to M5 submitted - Performance measures against milestones up to M5 accomplished. - Approval of next stage obtained.	Stage Gate passed based on evidence that: • The catalytic VAMMIT unit was fully commissioned and functional under both cold and hot conditions. • The safety dossier was accepted by the mine site and approval was given to proceed to hot commissioning and trials. • Catalysts had been tested for 36 hours, with no deterioration or moisture effect observed. High methane oxidation efficiency was obtained during the testing period
M6: Site trials and demonstration	17/6/2021	31/12/2022	Completion of site trials and demonstration with the following targets: - Self-sustaining minimum methane concentration: ~0.15% - Operation under ~750 °C - Methane oxidation efficiency ≥96% - Long-time operation: two months Operational data and site experience fully obtained with catalysts degrading rate analysed	Completed • Minimum operating methane concentration as low as 0.1 vol% • Average operating temperature of the bed as low as 450 °C • Oxidation efficiency up to 90 % • 476 hours of site trial tests • No catalyst degradation observed during the testing period

M6.1 Installation of upgraded blower unit	12/9/2022	28/2/2023	New blower and relevant modifications installed	Completed • The blower and Variable Speed Driver (VSD) were installed, commissioned and checked to be functional
M6.2 Final report	15/4/2023	20/10/2023	Completion of the final report	Completed • Draft final report submitted to CINSW for approval • Final report submitted
M6.3 Commissioning & Site trials of the upgraded pilot unit	1/7/2023	31/10/2023	Completion of site trials of the upgraded pilot unit	Completed • Calibration of sensors done • Four weeks of site trials with the new blower completed
M6.4 Submission of a draft supplementary report	1/9/2023	31/12/2023	Completion of the draft supplementary report to present - Results obtained following the blower upgrade - Decommissioning of the test facilities and site rehabilitation accepted by the mine representative	To be completed by the end of December 2023
M7 Decommissioning and reporting	1/12/2023	30/04/2024	Decommissioning of CSIRO VAM units and removed from the mine site	After consultation with South32, the decommissioning of the unit is expected to commence from December 2023 and complete by April 2024.

2 Design and construction of catalytic VAMMIT

2.1 Design of catalytic regenerative bed

The design of the novel VAM catalytic oxidation regenerative bed was based on almost two decades of our research experience and accumulated experimental data, including as listed below:

- VAM catalytic combustion test results for various commercial catalysts, obtained at QCAT Laboratories in 2001-2002.
- Performance data for the 25kW VAMCAT unit's catalytic combustor obtained from 2008 to 2017 at CSIRO laboratories and two mine sites.
- Thermal VAMMIT experimental data and operational experience obtained at CSIRO QCAT Laboratories in 2012 - 2013.
- Thermal VAMMIT site trial data and operational experience, site engineering design, construction and safety management experience obtained at Appin North in 2016-2017.

The CSIRO catalytic VAMMIT unit is a flow-reversal reactor for VAM catalytic oxidisation. It is primarily composed of a regenerative bed made of ceramic blocks and catalysts, two flow reversal valves and a start-up burner. The inclusion of catalysts as well as ceramic blocks in the regenerative bed is the major physical difference between a catalytic VAMMIT unit and a thermal unit.

During operation, the catalytic oxidation regenerative bed is virtually separated into three zones which include two preheating zones (A, top and B, bottom) and a catalytic oxidisation zone (C, middle). On start-up the preheating zone is preheated to a certain temperature by the start-up burner prior to switching to normal operation on VAM. Once the catalytic oxidation regenerative bed is preheated, the VA is fed into the reactor from bottom to top (forward flow process), heated up through zone B, and then reaches zone C where the VAM is catalytically oxidised to CO_2 releasing the oxidation heat. The resultant gas stream after passing zone C will subsequently flow through and heat up zone A and the low temperature exhaust is finally discharged to the atmosphere. After a certain interval, the direction of VA flow in the reactor is reversed, being fed from top to bottom (reverse flow process). In the reverse flow process, the VA flow is preheated in zone A and the VAM is oxidised in zone C and then heats up zone B for the next forward flow process. Thus, the catalytic version VAMMIT system can operate in a self-sustaining way to oxidise low concentration VAM without additional heat input. The interval for switching VA flow direction is largely dependent on the VAM conditions and the VAMMIT operational parameters such as VAM concentration, VA flow rate, etc.

In earlier work of CSIRO VAMCAT, it was found that Pd/Al_2O_3 was the most active catalyst for methane (CH_4) oxidation, and thus was selected for the catalytic VAMMIT prototype pilot unit. To achieve a CH_4 catalytic oxidation rate of 99%, results indicated that a preheated air temperature of 500 °C was required with a reasonable space velocity. However, as catalyst washcoating technologies have advanced over the years, the preheated air temperature required to meet over 99% CH_4 conversion has been lowered. In selection of the catalyst materials for catalytic VAMMIT, eight Pd/Al_2O_3 catalysts were tested at different methane concentrations, preheated air temperatures and space velocities at QCAT Laboratories in 2019. Overall, the catalyst selection test results showed that Pd/Al_2O_3 catalysts with advanced washcoating technology can be operated in a temperature range of 300-350 °C to achieve a methane conversion rate of over 99% at a reasonable space velocity, which is a very promising result and much lower than originally proposed (i.e. 450-750 °C). To align with enhanced catalyst performance, the bed design calculation was carried out assuming a preheated air temperature of 350 °C. The overall bed dimensions of the catalytic VAMMIT were kept the same as those of the existing thermal VAMMIT. The heights of the ceramic blocks and the catalytic layers were determined by calculating the mass and heat balance of the reactor with a VA flow rate of 0.25-1 Nm^3/s, VAM concentration of 0.2-1 vol% and flow switching time of 120 s.

2.2 Design of start-up burner

The start-up burner is applied to preheat the regenerative bed prior to feeding VA into the unit. Once the centre of the regenerative bed reaches the required temperature, the start-up burner is turned off, and VA is switched to flow into the regenerative bed for self-sustained operation of the VAMMIT unit. It is also very important to maintain flame stability at different combustion capacities. A high-speed swirl burner was designed and manufactured for the previous VAMMIT prototype unit.

To ensure the existing start-up burner would be suitable for the catalytic VAMMMIT unit, it was tested in hot trials to produce 300-450 °C hot air for preheating the catalytic VAMMIT unit. The start-up burner was successfully ignited at a blower shaft speed of 650 RPM and then increased up to 1800 RPM while the LPG flow rate was reduced from 120 to 60 LPM producing hot gas at 300-400 °C. As shown in Figure 1, the start-up burner was able to produce hot gas at about 380 °C to preheat the regenerative bed by carefully controlling the blower shaft speed, LPG flow rate, and opening of a manual valve and a pneumatic valve. The opening of both valves was adjusted to control the ratio of the first and second combustion air to stabilise the flame and minimise the flame temperature.

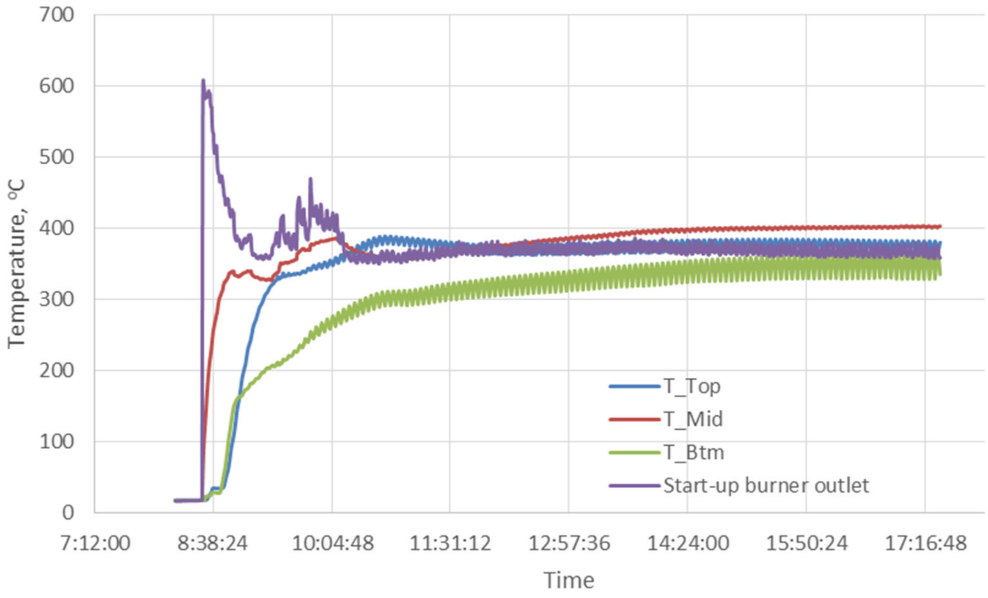

Figure 1 Temperature profiles of top, middle, bottom sections of regenerative bed and start-up burner outlet during preheating.

2.3 Design and installation of VA shaft snorkel and duct

During the previous site trails of CSIRO VAM units in 2016-2018, a split stream of VA was taken from a VA snorkel pipe (1.8 m in diameter) at WestVAMP. In late 2018, the snorkel for the WestVAMP plant was removed, so a new VA shaft snorkel and duct would be required for supply of VA to the catalytic VAMMIT. In order to avoid the potential impact of downtime due to maintenance of the mine's ventilation fans, two separate snorkel and duct sets were designed to connect directly to both mine ventilation shafts. Two butterfly valves were included and operated via chains by operators on the ground to open/close the corresponding VA shaft duct. To meet mine site regulations, the mechanical design of the new snorkel and duct system was reviewed and verified by a third party. Installation of snorkels and butterfly valves on both mine VA shafts was carried out in July 2019 during the maintenance of the mine's shaft fans to minimise interference with mine operations. The remaining VA duct piping was installed at the end of November 2019.

2.4 Construction of catalytic regenerative bed

The flow diverting section sits in the middle of the regenerative bed, consisting of CSIRO-developed ceramic blocks. The blocks were made of dense refractory castables and fabricated by the project team using CSIRO designed moulds. The produced blocks were calcined at high temperatures after moulding.

After customised catalysts were delivered to the WestVAMP site. The team commenced the site construction of the catalytic regenerative bed in November 2019. The construction of the catalytic bed was a key stage in building the catalytic VAMMIT pilot unit. Previous site trials of thermal VAMMIT systems showed that installation and stacking of honeycomb ceramic/catalytic blocks must be carefully carried out to ensure that the individual channels of honeycomb blocks are aligned and there are no sizeable gaps left between blocks and within the bed causing bypass in VA flow. The misalignment of block gas channels and the presence of bypass gas flows will adversely affect the VA flow distribution over the entire regenerative bed resulting in lowering the overall performance of the catalytic VAMMIT system.

2.5 Assembly of catalytic VAMMIT test unit

The pilot-scale catalytic VAMMIT test unit at the mine site, consists of three major components: (1) the catalytic VAMMIT prototype pilot unit, (2) the blower and piping to transfer VA and liquified petroleum gas (LPG) into the catalytic VAMMIT and (3) the site infrastructure (SI) skid. The SI skid acts as a safe ducting system connecting the catalytic VAMMIT with the mine shaft and is a CSIRO developed and patented system. Constructed in 2016, the SI skid has been tested and used for site trials of a suite of CISIRO VAM abatement prototype units including VAMCAT, thermal VAMMIT and VAMCAP.

2.6 Safety management

The safety management for site trials of the catalytic VAMMIT unit was assessed based on experience gained from site trials of the earlier thermal VAMMIT system. The VAM concentrations and operating temperatures for the catalytic VAMMIT were significantly lower than those for the thermal VAMMIT. This suggests that the risks associated with the operation of catalytic VAMMIT are lower than those for the thermal VAMMIT. The potential risks of the VAM abatement unit to the mine site are mainly managed by the SI system. Both prevention and suppression principles were applied in the design of the SI system. Interlocks with the Illawarra Coal mine's safety systems were also used to ensure safe operation.

3 Commissioning of catalytic VAMMIT

3.1 Function tests of catalytic VAMMIT prototype pilot unit

Before operation of the system, the following function tests were carried out to establish operational parameters.

- Service leak tests on LPG fuel lines
- Operational checks on all pneumatic valves and manual butterfly valves
- Human machine interface (HMI) control and monitoring system operational tests.
- VSD and blower test: limited by the pressure drop across the blower and the VSD current, the maximum blower speed was found to be around 2600 RPM. At this speed, the maximum deliverable flow rate of ventilation air was approximately 0.74 m^3/s under ambient conditions. It was expected that the flow rate would drop to some extent due to increased pressure drop across the catalytic bed under hot conditions.
- Start-up burner ignition test with LPG and fresh air: ignition conditions for future tests were determined as: blower speed 650 RPM, LPG flow rate 120-200 L/min.

3.2 Calibration and verification of trip-related sensors and instruments

All the safety related electrical transmitters and sensors incorporated into the tripping system were calibrated and verified by a third party accredited by the National Association of Testing Authorities (NATA) as required by mine site regulations. The sensors include a carbon monoxide sensor interlocked with the coal mine safety system, two laser-type methane detectors, one infrared methane sensor, temperature transmitters and pressure transmitters. In addition, two actual VAM gas samples were collected and analysed by Coal Mine Technical Service to verify the readings of the methane sensors after calibration.

3.3 Measurement of VAM concentrations

The catalytic bed was first preheated to its working temperature using the blower and burner operating conditions determined above and then VA with a desired VAM concentration was fed into the catalytic VAMMIT unit for operation and performance testing.

Hot commissioning was started with low concentration levels of VAM to avoid overheating of the catalyst. Laser-based methane sensors continuously measured VAM concentration. Methane concentration in the actual VA ranged between 0.235 and 0.46 vol% during the testing period. To dilute methane concentrations in the actual VA, the VA was mixed with fresh air. A pneumatically actuated control valve was used to control the addition of fresh air to the VA.

The following concentrations were continuously monitored and recorded for safety management and to determine the methane oxidation efficiency: the methane concentration of the actual VA (measured upstream of the gas mixer), the methane concentration in the diluted VA (measured downstream of the gas mixer) and the methane concentration of the exhaust gases. If the methane concentration in the VA exceeded 1.25 vol%, an emergency shutdown would be triggered. The emergency shutdown procedure involved safe venting of process gases and immediate shut-off of fuel flow to the unit.

To doubly confirm the accuracy of the laser-based methane sensor measurements, gas samples from the VA feed stream and exhaust gas stream were periodically collected and analysed on site by gas chromatography (GC).

3.4 Data acquisition and analysis

All parameters were recorded at 20 second intervals during the trials. The catalytic bed temperature was measured by a number of thermocouples while the pressure drop across the bed was measured by a differential pressure transmitter. Some of the raw data was processed to filter out noise.

To quantify catalyst performance, the VAM oxidation efficiency was calculated using the following equation:

$$Methane\ oxidation\ efficiency = (1 - \frac{Outlet\ methane\ concentration}{Inlet\ methane\ concentration}) \times 100\%$$

In addition to the laser-type methane detectors, inlet and outlet gas streams were sampled and then periodically analysed with an Agilent 490 Micro GC.

Table 2 summarises the three parameters used as criteria to assess the performance of the catalytic VAMMIT unit under various operating conditions which will be discussed in the next chapter. The catalytic VAMMIT unit should be operated over a sustained period under constant operating conditions to better understand the longer-term variation of these parameters. The self-sustainability of a catalytic VAMMIT should also be assessed employing multiple criteria if applicable, instead of a single criterion as it may provide contradictory conclusions.

Table 2 Performance criteria for the self-sustaining operation of the catalytic VAMMIT unit

Parameters to be monitored	**Symptoms of positive self-sustaining operation**	**Symptoms of negative self-sustaining operation**	**Notes**
Differential pressure (DP) across catalytic bed	Stabilised or increasing	Decreasing	A stabilised or increasing DP across the bed indicates that the overall bed temperature is stable or increasing. However, an increase of DP could be also caused by dust decomposition if the bed temperature does not increase.
Catalyst bed temperature	Stabilised	Increasing or decreasing	If the temperature increases, the unit may behave as a thermal version and the catalyst may lose its activity. If catalyst bed temperature keeps dropping, it means the catalyst is cooling down and may be extinguished.
Methane oxidation efficiency	Stabilised or increasing	Decreasing	Decreasing of methane oxidation efficiency means increasing amounts of methane are unoxidised and indicates that the heat balance is difficult to establish.

4 Site trials of catalytic VAMMIT

Table 3 summarises the conditions and key results of site trials of the catalytic VAMMIT polit unit. Each hot trial was assessed against the three performance criteria as shown in Table 2. It should be noted that the inlet methane concentrations measured by the GC were 0.02-0.03 vol% lower than the inlet methane concentration values measured by the laser-type methane detector. While this discrepancy is acceptable across the full measurement span of the methane sensors and has no adverse impacts on safety management, it should be considered when determining the accurate minimum methane concentration required for self-sustaining operation. The discussion below uses GC values to represent actual methane concentrations.

For a given testing condition (i.e., specific VA flow rate and VAM concentration), reactor heat management is primarily determined by the flow switching time. The switching time was initially preset to 120 s, based on the operation of the earlier thermal VAMMIT unit. However, it was found that this setting required adjustment according to each specific testing condition in order to maintain the catalytic bed temperature during hot trials. Stable operation of the unit could not be achieved using a fixed switching interval. The temperature variation of the catalyst layers could exceed the range of 400-800 °C, leading to either extinguishing the reactor bed or over-temperature that causes lowering catalytic activity of VAM oxidation.

To overcome this problem, the switching time was manually adjusted to correct fluctuations in the bed temperature. However, this approach was unsuccessful as the response time was too long and significant temperature fluctuations were observed. Subsequently, an auto-control algorithm was developed, and the switching time was determined by the average temperatures of the ceramic beds adjacent to the inlet/outlet pipelines of the unit. This control algorithm was aimed at maintaining a relatively constant heat flow exiting the reactor. The switching time ranged from 50 s to 250 s, depending on the VAM concentration and VA flow rate. This approach was successful and was able to minimise temperature fluctuations across the catalytic bed, leading to more stable unit operation.

Table 3 Summary of conditions and key results from catalytic VAMMIT site trials

	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6	Test #7	Test #8	Test #9	Test #10	Test #11
Date	17-18/06/ 2021	18/06/ 2021	20/06/ 2021	5-6/04/ 2022	6-7/04/ 2022	7-8, 28-30/04/2022	30/04-2/05/2022	31/05-3/06/2022	29/07-02/08/ 2022	5-7/08/ 2022	7-9/08/ 2022
Inlet CH_4 concentration by laser detector, %	0.105	0.32-0.46	0.15	0.106-0.153	0.153-0.18	0.153	0.224-0.248	0.129	0.153	0.153	0.153-0.334
Inlet methane concentration by GC, %	0.08-0.09	0.29-0.38	0.11-0.12	0.08-0.12	0.13	0.13	0.18-0.22	0.08-0.11	0.13	0.13	0.13-0.28
Outlet CH_4 concentration by infrared sensor[1], %	0.008	>0.06	0.006	0.003	0.004	0.012	0.023	0.025	0.03-0.036	0.028-0.045	0.043-0.061
Outlet CH_4 concentration by GC, %	0.007	>0.058	0.008	0.0129	0.013	0.021	0.03	0.02	0.013-0.018	0.015-0.018	0.02-0.033
VA flow rate, Nm^3/s	0.5	0.5	0.5	0.5	0.5	0.67	0.67	0.5	0.5	0.33	0.67
switching time, seconds	120	120-960	90-120	120	120	120	100-380	Auto control	Auto control	Auto control	Auto control
Performance criteria											
DP across catalytic bed	*Decreasing*	*Increasing*	*Decreasing*	*Decreasing*	*Stabilised*	*Decreasing*	*Fluctuating*	*Stabilised*	*Stabilised*	*Stabilised*	*Stabilised*
Catalyst bed temperature	*550-480^{o}C, Decreasing*	*>800^{o}C, Increasing*	*<800^{o}C, decreasing*	*500-440°C decreasing*	*~480^{o}C, Stabilised*	*~480^{o}C, Stabilised*	*480-580°C Fluctuating*	*~440^{o}C, Stabilised*	*~480^{o}C, Stabilised*	*600-500^{o}C, decreasing*	*550-480^{o}C, Stabilised*
Methane oxidation efficiency, %	*~91%, stabilised*	*<80%, decreasing*	*91-93%, stabilised*	*84-90%, stabilised*	*85-90%, stabilised*	*84-89%, Stabilised*	*82-90%, stabilised*	*78-87%, stabilised*	*~86-90%, stabilised*	*85-90%, stabilised*	*~85-89%, stabilised*
Self-sustainability	**Not confirmed**	**Negative**	**Not confirmed**	**Not confirmed**	**Positive**	**Positive**	**Negative**	**Positive**	**Positive**	**Not confirmed**	**Positive**
1: Readings taken at the end of trial test under each testing condition											

4.1 Test #1: 0.08 vol% VAM and 0.5 Nm^3/s VA

In the following sections, the key findings for each test are presented in dot point form followed by a detailed analysis of the test.

- With a VA flow rate of 0.5 Nm^3/s, the VAM concentration was set at 0.08 vol% by mixing with fresh air.
- Over 13 hours of operation, the methane oxidation efficiency was approximately 91.2%.
- The average catalytic bed temperature decreased slowly and reached 489 °C at the end of the test.
- Significant temperature fluctuations were observed in one catalytic layer, suggesting a potential issue with bed structure within that layer thus impacting VA flow and temperature distribution.

The first catalytic VAMMIT unit site trial commenced on 17th June 2021. Pre-heating commenced at 7am but was paused for approximately 4 hours due to the loss of the compressed air supply from the mine. Pre-heating was resumed at 2pm and completed at around 6pm. VA was diluted with air to contain 0.08-0.09 vol% CH_4 measured by GC (0.105 vol% by laser detector) and 0.5 Nm^3/s of diluted VA was fed into the catalytic VAMMIT unit from 6pm to 7am the next day.

The first trial results for the whole testing period are presented in Figure 2a, and for the period of 6:30-6:50am in Figure 2b. It is noted that the inlet and outlet CH_4 concentrations were measured continuously by laser and infrared sensors and are plotted in Figure 2. The inlet and outlet gas samples were also collected every 4-5 hours and analysed by a micro-GC. The VA flow rate was maintained at 0.5 Nm^3/s and the flow direction was reversed every 120 s which was predetermined from the thermal VAMMIT operation. The timing of the flow reversal is indicated by the vertical dashed lines in Figure 2b. As shown in Figure 2b, when the flow direction was reversed the outlet methane concentration immediately increased slightly and then gradually dropped to its original value. This trend is caused by a negligible amount of fresh VAM bypassing the catalytic bed and exiting through the exhaust pipe when the flow is reversed. As such, it is preferrable to have a longer switching time to minimise methane escape, given that the unit can maintain its operation. The switching time can be varied depending on VAM concentrations and VA flow rates.

During the 12-hour period of operation, the catalyst worked stably and efficiently, achieving an average methane oxidation efficiency of 91.2%. As can be seen in Figure 2a gradual decreasing trends were, however, observed in the pressure drop across the bed, the centre bed temperature and flue gas temperature. However, the outlet methane concentration remained stable within the range 0.007-0.008 vol% as confirmed by GC measurements. Although the average catalytic bed temperature decrease was slow in the last 20 mins (i.e., from 495 to 489 °C) as shown in Figure 2b, this indicates that a thermal balance had not yet been fully achieved. As the catalytic bed temperature was still high enough (> 400 °C at which 100% CH_4 conversion was expected from catalyst screening results), self-sustained operation could potentially be achieved under this test condition if the testing period was prolonged. The starting temperature of the catalytic bed was about 550 °C which might be too high to be maintained with the amount of heat generated by the catalytic oxidation of 0.08 vol% CH_4.

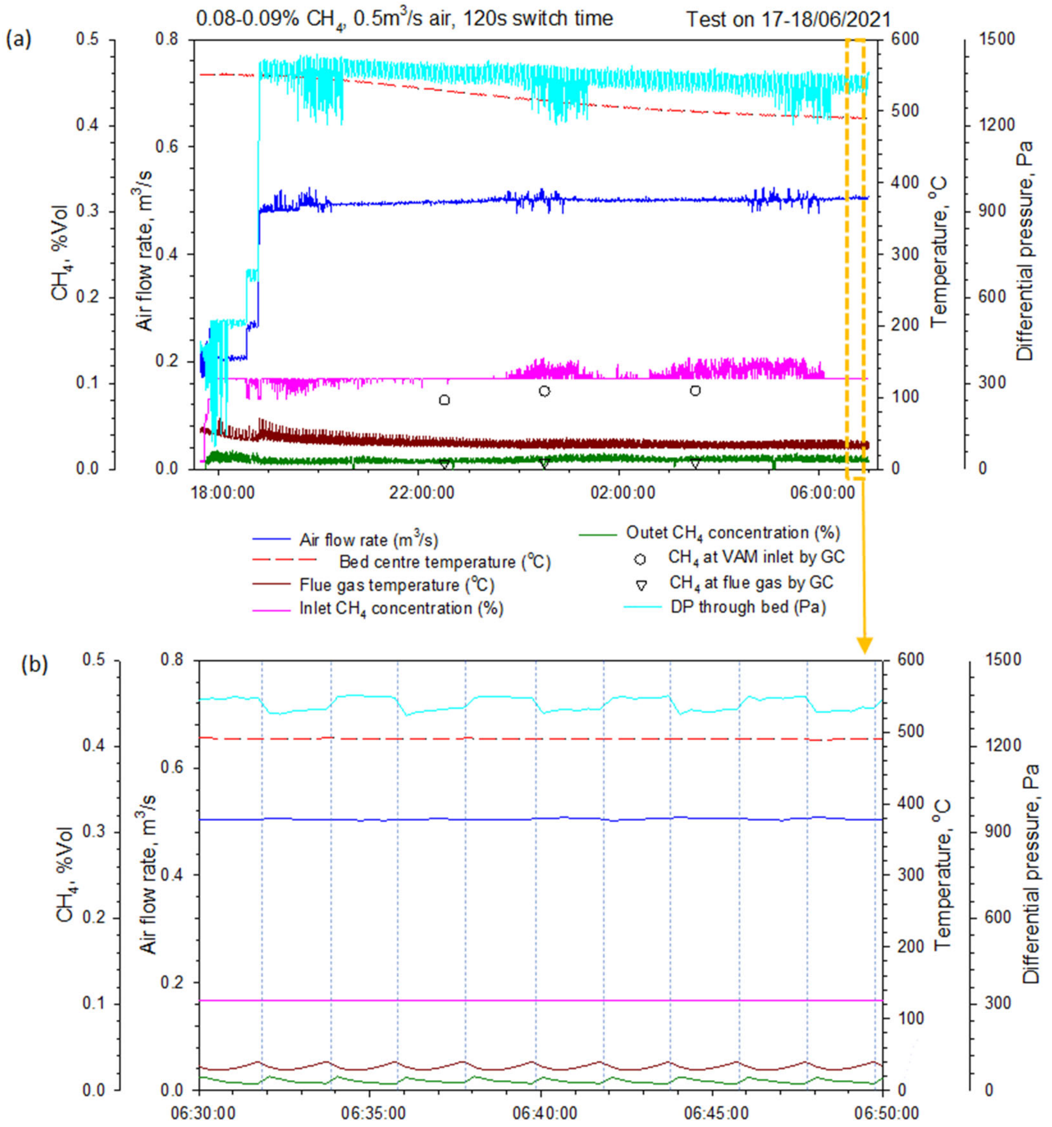

Figure 2 (a) Results of site trial test #1 with 0.08-0.09 vol% VAM and 0.5 Nm^3/s VA, and (b) enlarged results for the period of 6:30-6:50am. Broken vertical lines indicate the timing of flow reversal.

4.2 Test #2: undiluted VAM and 0.5 Nm^3/s of VA

The key findings are:

- With a VA flow rate of 0.5 Nm^3/s, actual VA with 0.29-0.38 vol% CH_4 was introduced to the unit without dilution.
- Over 12 hours of operation, the oxidation efficiency was 92% with hotspots exceeding 800 °C in the catalytic blocks, which limited the unit's operation.
- A prolonged switching time of up to 960 seconds was used for catalyst cooling, but this led to the extinguishing of some catalyst blocks, evidenced by their low temperatures (i.e. <300 °C) and reduction of overall methane oxidation efficiency (i.e. <80%).
- Additional heat management measures may be needed to process high VAM concentrations.

Following hot commissioning with diluted VA containing 0.08-0.09 vol% CH_4 (by GC) (0.105 vol% by laser detector), fresh air was switched off and undiluted VA was introduced to the catalytic VAMMIT unit at around 7:50am on 18 June 2021. During the test period, VAM concentrations were measured varying in the range of 0.32-0.46 vol% by the laser methane detectors and of 0.29-0.38 vol% by the GC. The VA flow rate was maintained at 0.5 Nm^3/s while the flow switching period was varied between 120 s and 960 s in order to control the bed temperature and achieve thermal balance. The hot trial results under this condition are presented in Figure 3.

As soon as actual VA was introduced, the catalyst layer temperatures started to increase (not shown here). For instance, the catalyst temperatures in one catalytic layer exceeded 700 °C at 9am. This indicates that the reaction heat resulting from methane catalytic oxidation accumulated inside the catalytic bed. To take more heat away from the reactor, the flow switching time was gradually increased from 120 to 480 s at 11:40am to move the central hot zone towards the bottom or top of the bed. However, the catalyst temperature kept increasing with some hotspots observed and the temperatures were around 800 °C. It should be noted that during this period, approximately 92% of VAM was oxidised by the catalyst. The maximum design bed temperature was 750 °C and the maximum catalyst service temperature was 950 °C. To avoid possible catalyst deterioration at temperatures above 800 °C, fresh air was introduced into the catalytic VAMMIT unit at 12pm and then the catalytic bed started to cool down. As the bed temperature dropped below 600 °C at 1:30pm, actual VA was again fed into the catalytic VAMMIT unit and the flow switching time was gradually increased to 960 s to examine the thermal response. While a temperature increase was still evident in most catalyst layers, extinguished catalytic reaction was observed in some areas. The catalysts at the top corner between the flow divertor and burst disc gradually extinguished from 4pm due to over cooling. As a result, the VAM oxidation efficiency decreased to below 80%.

The results show that the bed temperature responded unevenly to actual VA and as a consequence gave rise to thermal unbalance in the unit. These results suggest that when the catalyst temperatures in each layer and location are different, it would be difficult to achieve thermal balance by only regulating the flow switching time. As the current design does not have an effective way to remove heat from the catalytic bed in a timely manner, regulation of the inlet VAM concentration is required for the current catalytic VAMMIT unit to be sustainably operated. When treating actual VA with more than 0.3 vol% CH_4, the heat balance can be still improved, to some extent, by constantly adjusting the flow switching time. However, a prolonged flow switching time may cause parts of the catalytic bed to extinguish. Overall, a new bed design for this catalytic thermal oxidation process should take into account the distinctive heat transfer characteristics of ceramic blocks and catalytic blocks, along with implementing additional heat management measures if necessary.

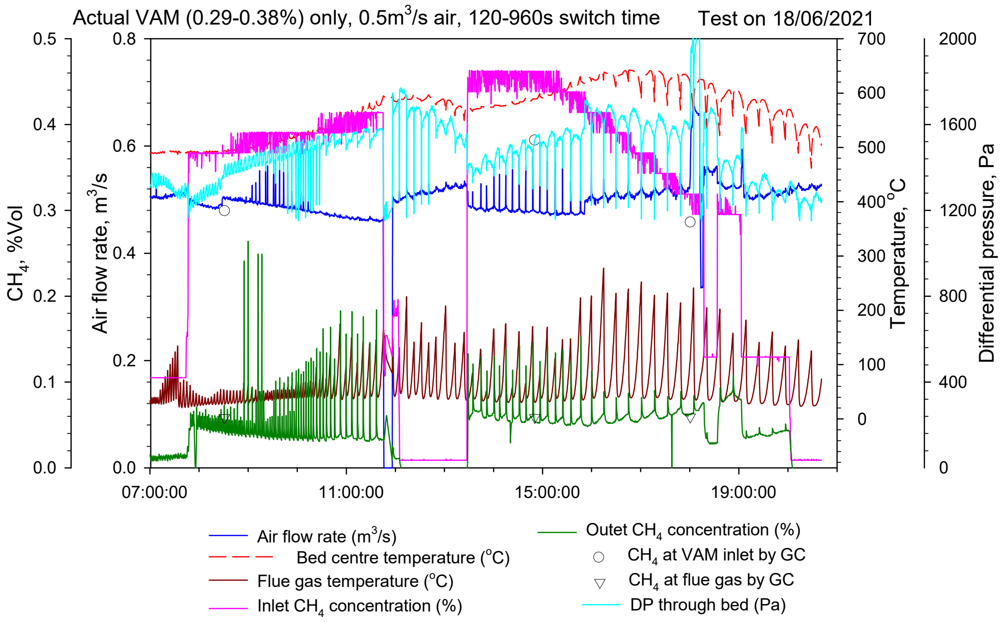

Figure 3 Results of site trial test #2 with 0.29-0.38 vol% VAM and 0.5 Nm^3/s VA.

4.3 Test #3: 0.12 vol% VAM and 0.5 Nm^3/s VA

The key findings are:

- The unit was tested with 0.12 vol% VAM for 8 hours and the oxidation efficiency was over 92%.
- The switching time was reduced from 120 s to 90 s to maintain the catalytic bed temperature.
- A longer testing time was needed to confirm the sustainable operation of the unit.

Learning from the response of the catalytic VAMMIT unit to actual VA, it was decided to dilute the actual VA to find an optimum range of methane concentrations. Keeping the VA flow rate at 0.5 Nm^3/s, this trial was carried out with diluted VA containing 0.12 vol% CH_4 (by GC, 0.15 vol% by laser sensor) on 20th June 2021. The results are presented in Figure 4. For the first 1.5 hours, the VA flow rate was maintained at 0.25 m^3/s in order to achieve a more uniform temperature distribution across the catalyst layers. From 2:30pm, the VA flow rate was increased to 0.5m^3/s.

During the period of 2:30pm to 6:30pm, the flow switching time was set to 120 s. While the pressure drop across the catalytic bed was stable, average flue gas temperature decreased slightly but fluctuated continuously. To retain more reaction heat in the reactor, the flow switching time was reduced from 120 to 90 s at 6:30pm. This seemed to stabilise the flue gas temperature. Over the testing period, the outlet methane concentration was about 0.009 vol%, representing over 92% methane oxidation efficiency. Nevertheless, a longer operation period is required in order to confirm that the catalytic VAMMIT unit can be self-sustainable with 0.12% VAM. This condition will be further tested in the next phase trials. Having a more uniform temperature distribution across the catalytic bed at the start was found to be a good practice to manage the thermal balance. This suggests that the bed temperature may need to be slowly increased up to the target catalytic reaction temperature by adjusting the pre-heating process.

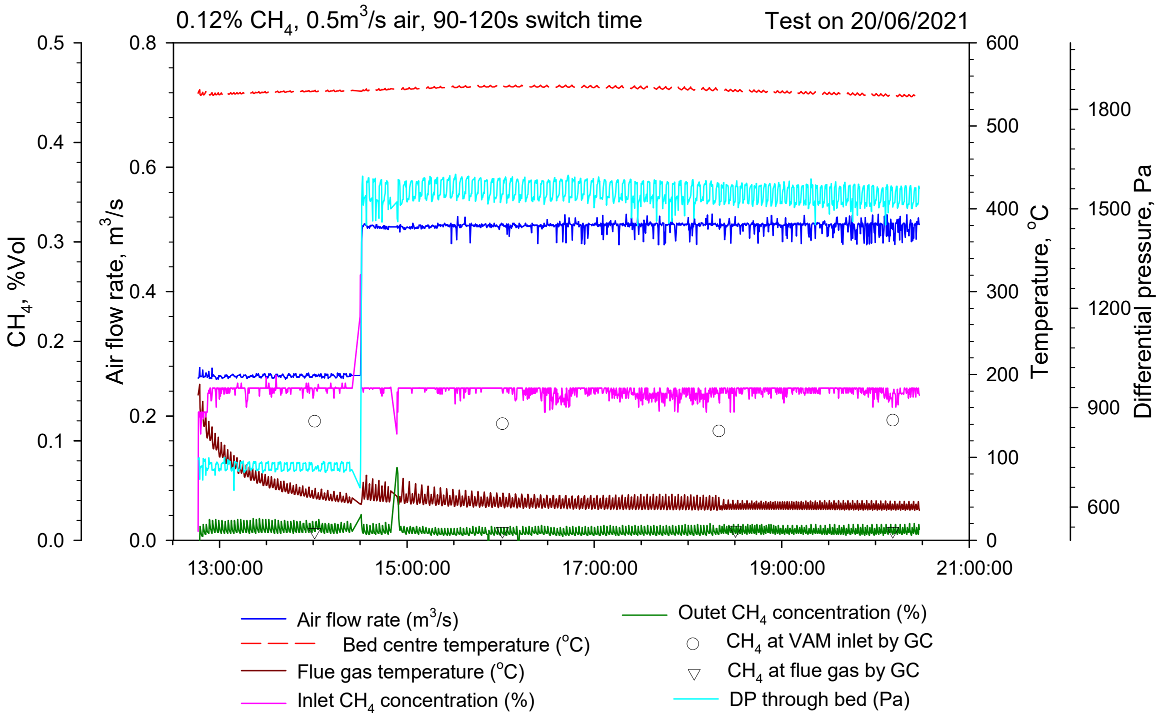

Figure 4 Results of site trial test #3 with 0.12 vol% VAM and 0.5 Nm^3/s VA.

4.4 Test #4: 0.08-0.12 vol% VAM and 0.5 Nm^3/s VA

The key findings are:

- The unit was tested for 19 hours with 0.08-0.12 vol% VAM and 0.5 Nm^3/s and the oxidation efficiency was 84-90%.
- Self-sustaining operation of the unit was not confirmed as the bed temperature was slowly but continuously dropping during the test period.

The fourth hot trial test was carried out on 5-6 April 2022. As part of the ongoing process to find an optimum range of VAM concentrations for the current unit, the actual VA was diluted with air to 0.08-0.12 vol% CH_4 (by GC) which matches the conditions between tests #1 and #3. The results are shown in Figure 5. Overall, the catalytic bed temperature decreased during the testing period although the feed methane concentration was increased from 0.09 to 0.12 vol% for about 4 hours. The methane oxidation efficiency gradually dropped from 90% in the beginning to 84% in the end of this test condition. Although it is not clear whether the unit can be operated under this condition in a self-sustained manner, the inlet methane concentrations with the given VA flow rate (0.5 Nm^3/s) may not be sufficient to keep the bed temperature stable as the bed temperature was slowly but continuously dropping. As further tests were needed, a similar condition was tested from 31/05 to 3/06/2022 (test #8) to confirm the self-sustaining operation of the pilot unit.

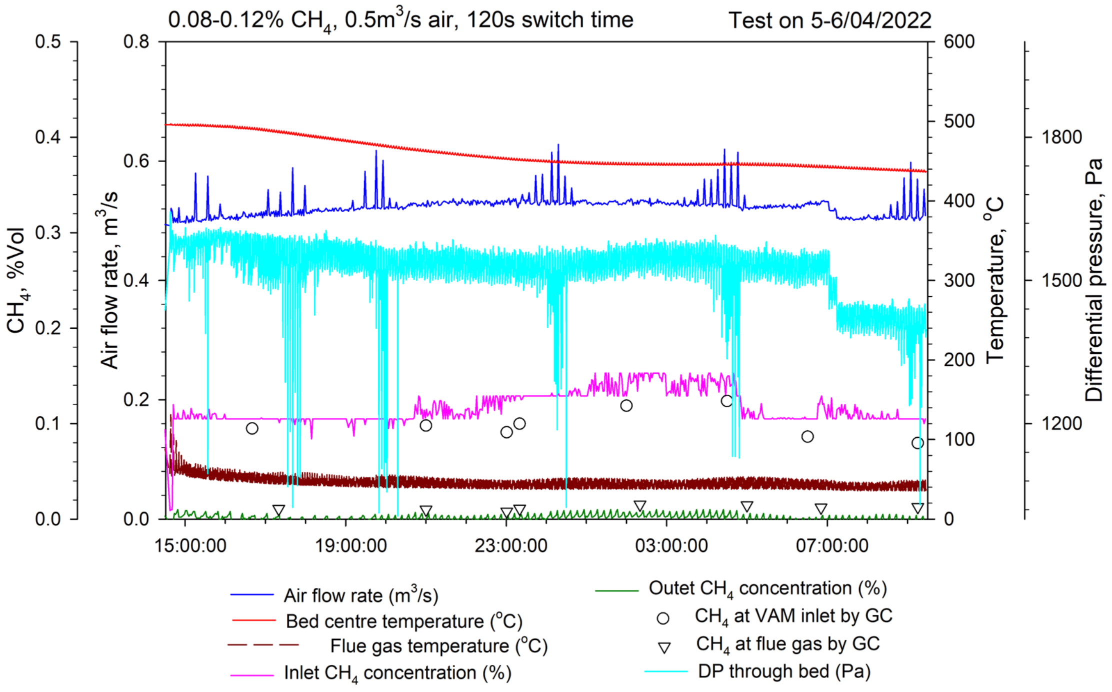

Figure 5 Results of site trial test #4 with 0.08-0.12 vol% VAM and 0.5 Nm^3/s VA.

4.5 Test #5: 0.13 vol% VAM and 0.5 Nm^3/s VA

The key findings are:

- The unit was tested for 35 hours with 0.13 vol% VAM and 0.5 Nm^3/s VA and the oxidation efficiency was 85-90%.
- The bed temperature was stabilised at about 480 °C and the unit could maintain its operation.

Following the hot trial with 0.08-0.12 vol% VAM and 0.5 Nm^3/s VA (test #4), the feed methane concentration was increased to around 0.13 vol% while the VA flow rate remained unchanged by reducing the flow rate of air, and the test results are shown in Figure 6. The centre bed temperature increased for the first 10 hours as more heat was generated and stored in the bed. Also, the VAM oxidation efficiency increased to 90%, suggesting that the centre bed temperature played an important role. From 10pm on the 6th of April, the centre bed temperature and exhaust gas temperature were very stable over a period of about 20 hours. It can be concluded that the catalytic VAMMIT unit can self-sustain at VAM concentration of 0.13 vol% and VA flow rate of 0.5 Nm^3/s. It is worthwhile noting that the centre bed temperature and the exhaust gas temperature were significantly affected by the feed methane concentration if the switching time is fixed (i.e., 120 s in this test), indicating that the switching time needs to be optimised to control the overall heat balance of the catalytic VAMMIT unit. It is noted in Figure 6 that significant interference was observed every five hours in the air flow rate and pressure drop measurements. The source of the interference is unknown but could be related to external mine site activities as it was not related to VAMMIT operation.

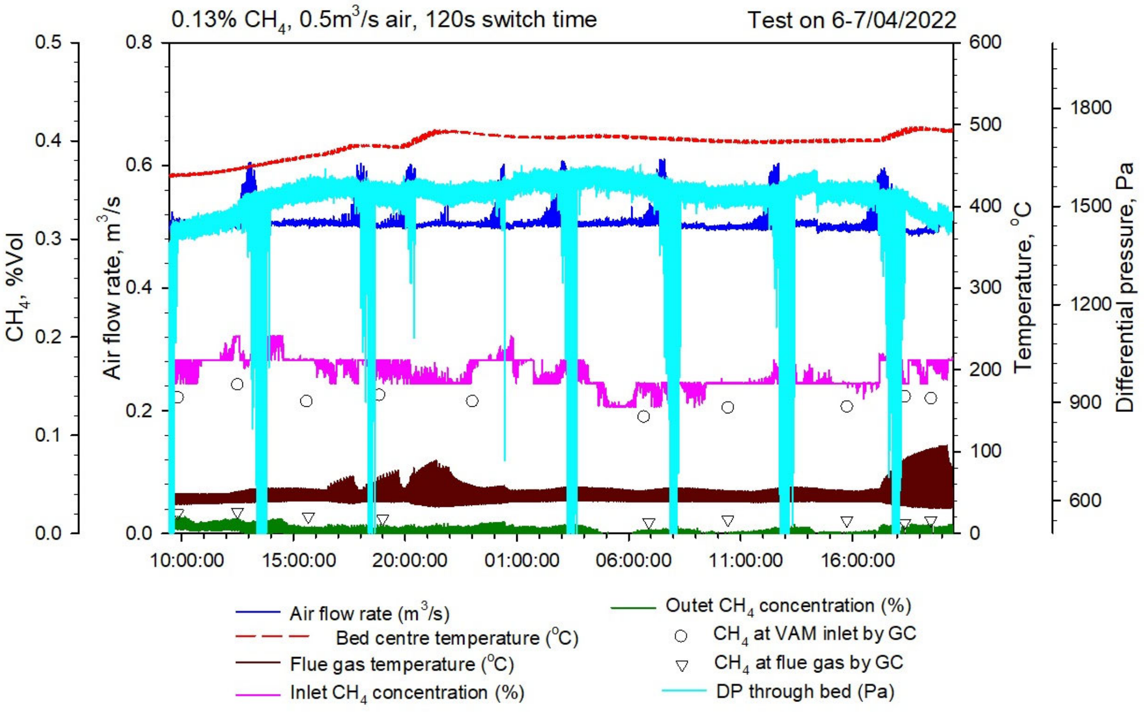

Figure 6 Results of site trial test #5 with 0.13 vol% VAM and 0.5 Nm^3/s VA.

4.6 Test #6: 0.13 vol% VAM and 0.67 Nm^3/s VA

The key findings are:

- The unit was tested for 58 hours with 0.13 vol% VAM and 0.67 Nm^3/s VA in two separate periods and the oxidation efficiency was 84-89%.
- The parameters of the two tests were similar, indicating stable operation of the unit.
- The unit can maintain self-sustaining operation with these conditions, and it represents one of the lowest VAM concentrations treated in a pilot-scale unit.

From previous tests, it was found that the catalytic VAMMIT unit achieved self-sustaining operation at a VAM concentration of 0.13 vol% and VA flow rate of 0.5 m^3/s. If the methane oxidation efficiency is not compromised, it is highly desirable to process higher VA flow rates which means smaller unit size and lower cost. To investigate the effect of VA flow rates on unit performance, keeping the VAM concentration at 0.13 vol%, the VA flow rate was increased to a maximum of 0.67 Nm^3/s which was the maximum achievable, restricted by inlet pipe diameter and blower power.

Two tests were carried out on 7-8 April and 28-30 April 2022, and the results are shown in Figure 7. The centre bed and flue gas temperatures kept gradually decreasing but still indicated stable performance as can be seen in Figure 7(a). VAM oxidation efficiency was 86 % at 10:30pm on the 7th of April and it decreased to 83 % at 12pm on the 8th of April. As one of the dampers was damaged around mid-day on the 8th of April, the test was terminated. The test duration was not long enough to conclude whether the unit is self-sustainable under this testing condition. As a result, the same condition was tested again from 28 to 30 April 2022. The centre bed temperature dropped slightly at the beginning and then stabilised at about 480 °C for over 31 hours. The VAM oxidation efficiencies were in the range of 84-89%. Hence, the unit can be self-sustained with VAM concentration of 0.13 vol% with VA flow rate of both 0.5 and 0.67 m^3/s.

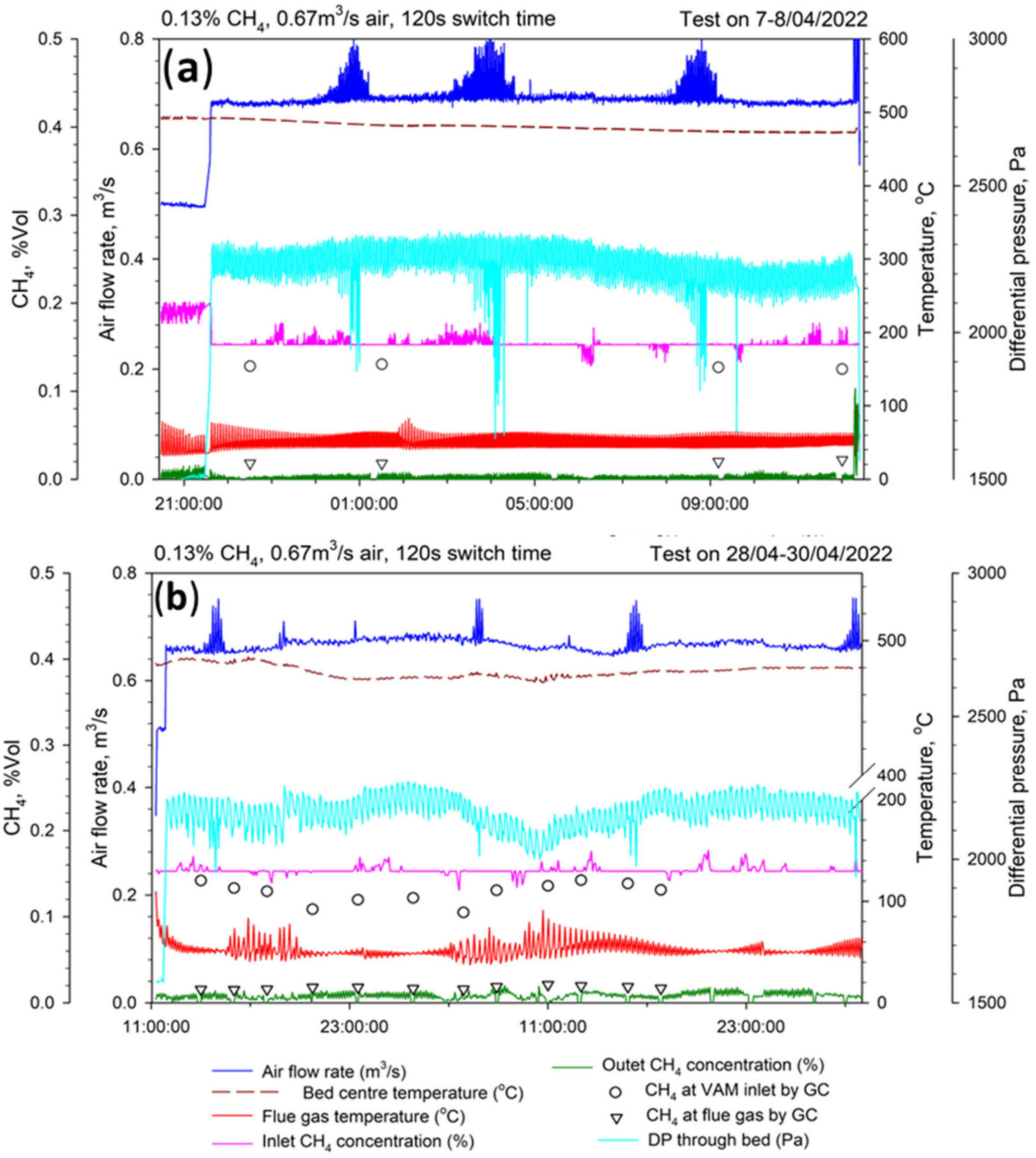

Figure 7 Results of site trial test #6 with 0.13 vol% VAM and 0.67 Nm^3/s VA.

4.7 Test #7: 0.18-0.22 vol% and 0.67 Nm^3/s VA

The key findings are:

- The unit was tested for 59 hours, and the efficiency was 82-90%.

- The catalytic bed temperature fluctuated in the range of 480-580 °C and hot spots over 800 °C were observed.
- Increased switching time led to the extinguishing of some ceramic blocks, suggesting those extinguished blocks could have issues with ununiformed VA flow and low catalytic activity.
- Current heat management measures were not adequate for the unit to process this condition.

As less dilution of VA with air can increase the VA treatment capacity of the unit, keeping the inlet flow rate at 0.67 Nm^3/s, the actual VA was diluted with air to contain 0.18-0.22 vol% CH_4 and then fed to the unit from 30 April to 2 May 2022. Overall, unlike other previous test conditions with lower VAM concentrations, this test condition needed more care to maintain the catalytic bed temperature and avoid overheating the catalyst. In particular, some hot spots of over 800 °C in the catalyst layers were observed. In response the VA inlet was shut off periodically and fresh air was introduced to cool the catalytic bed to keep the catalyst active. As shown in Figure 8, the pressure drop along the reactor and the exhaust gas temperature fluctuated, reflecting the variation of inlet VAM concentration and VA flow rate, even though the oxidation efficiencies were in the range of 82-90%. In contrast with the results of test #5, where the methane oxidation efficiency increased from 85% to about 90% when the catalytic bed temperature was increased from 440 to 480 °C, it did not further improve the methane oxidation efficiency. This might be due to the prolonged switching time leading to the extinguishing of some catalytic blocks.

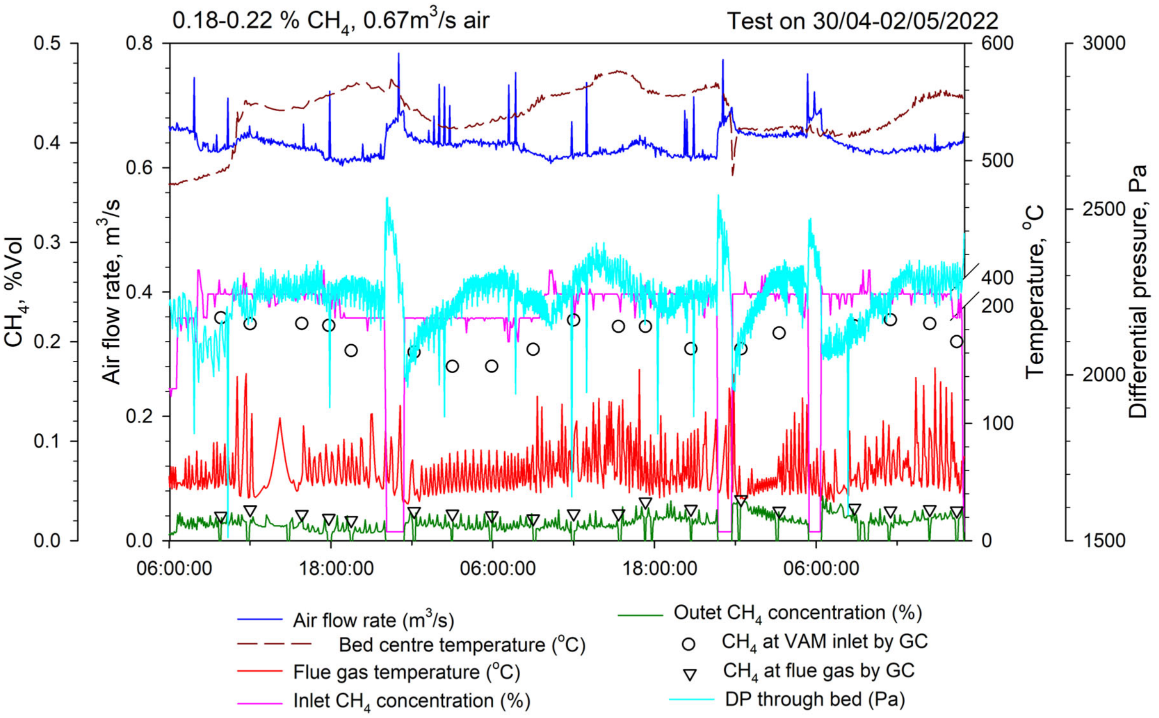

Figure 8 Results of site trial test #7 with 0.18-0.22 vol% VAM and 0.67 Nm^3/s VA.

4.8 Test #8: 0.08-0.11 vol% VAM and 0.5 Nm^3/s VA

The key findings are:

- The unit was operated for 81 hours and this test confirmed that the unit can be self-sustaining with about 0.1 vol% VAM and 0.5 Nm^3/s VA, which is the lowest VAM concentration oxidised in a pilot-scale unit to date.
- Auto-control of the switching time can maintain the catalytic bed temperature more effectively.
- Shorter switching times set by the auto-control led to a reduction in oxidation efficiency, which was caused by the VA bypassing through the exhaust pipe when the flow direction was reversed.

To confirm the results of test #4 with a longer period of operational time, the same test conditions (0.08-0.11 % VAM and 0.5 Nm^3/s VA) were applied and the unit was operated continuously for 3.5 days. The key results are shown in Figure 9. For the first 10 hours, the VAM concentration was maintained at 0.08 vol% and the switching time was set to 60 s. As the bed temperature kept decreasing, it was likely that the unit performance could not be sustained at this methane concentration. The methane oxidation efficiency decreased from 87% to 78% in 9 hours.

Hence, to obtain sustainable test results, the methane concentration was increased to 0.11 vol%. As well, rather than the switching time being fixed, it was automatically controlled to stabilise the operation. It was then found that the bed and exhaust gas temperatures stabilised at 440 °C and 30-40 °C, respectively for 68 hours without any intervention. The oxidation efficiencies were in the range of 78-85%.

It is noted that some drift occurred in the outlet methane sensor signal as can be noticed in Figure 9. The oxidation efficiency was, however always calculated using the GC data. The overall efficiency in this test was lower than that of test #4 although both tests were operated under similar conditions except for the flow switching time. It is likely due to the sampling error caused by the reduced switching time. As mentioned in section 4.1, VA can bypass the catalytic bed and exit through the exhaust pipe when the flow is reversed. The switching time for test #4 was fixed at 120 seconds whereas it was varied for test #8, being mostly less than 120 seconds. The proper sampling of the exhaust gas for GC analysis was difficult because of the reduced and varied switching time which was auto controlled to manage the catalytic bed temperatures. Hence, the methane concentrations in the exhaust pipe were higher in this test (#8) than Test #4, giving rise to lower oxidation efficiencies. Nevertheless, it can be concluded that this unit can be operated in a self-sustained manner with VAM concentration of about 0.11 vol% and VA flow rate of 0.5 Nm^3/s.

In general, a CFRR can treat VAM as low as 0.1 vol% (US EPA 2000; Wang et al. 2010), as it can be operated at a much lower operational temperature than TFRR. However, to the best of our knowledge, this test represents the first successful pilot-scale demonstration confirming that a CFRR can be operated at 0.1 vol% VAM, compared to at least 0.3 vol% for TFRR.

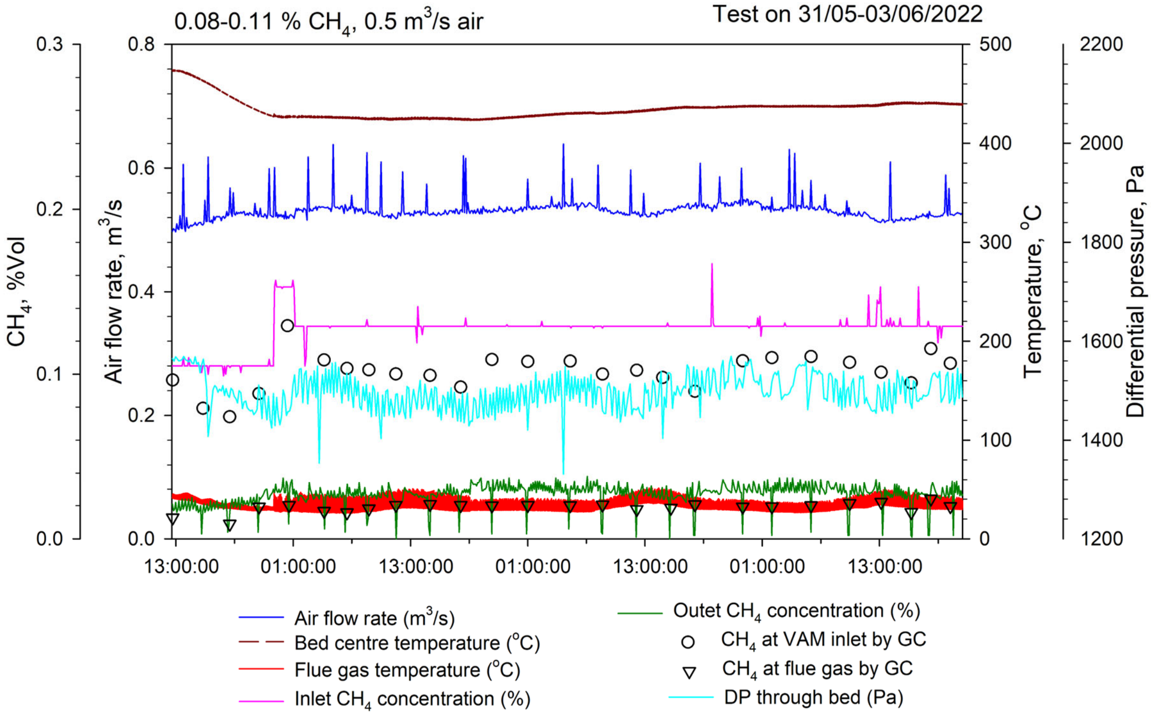

Figure 9 Results of site trial test #8 with 0.11 vol% VAM and 0.5 Nm^3/s VA.

4.9 Test #9: 0.13 vol% VAM and 0.5 Nm^3/s VA

The key findings are:

- The unit was tested for 88 hours with 0.13 vol% VAM and 0.5 Nm^3/s VA.
- The operation was self-sustaining and the oxidation efficiency was 86-90%.
- The operational parameters were similar to those of Test #4 although an auto-control algorithm was applied for bed temperature control.

Further testing was carried out to check the effectiveness of flow switching time control by auto mode. With diluted VAM concentration of 0.13 vol% and VA flow rate of 0.5 Nm^3/s, the centre bed temperature of the unit was stabilised from 560 to about 480 °C in 23 hours. Methane oxidation efficiencies were in the range of 86-90% as can be seen in Figure 10. With the given conditions, the operation was then self-sustaining without any intervention, confirming the effectiveness of the auto-control mode. Moreover, the catalytic bed temperature was nearly identical to that seen in test #5. The switching time ranged from 95 to 122 s, which on average was slightly lower than the constant switching time (120 s) used in test #5. More reaction heat can be retained in the reactor in this case. Learning from test #8, great care was taken when sampling the exhaust gas for GC analysis. This confirms that the lower oxidation efficiency of test #8 compared to test #4 was caused mainly by the VA bypassing through the exhaust pipe when the flow direction was changed.

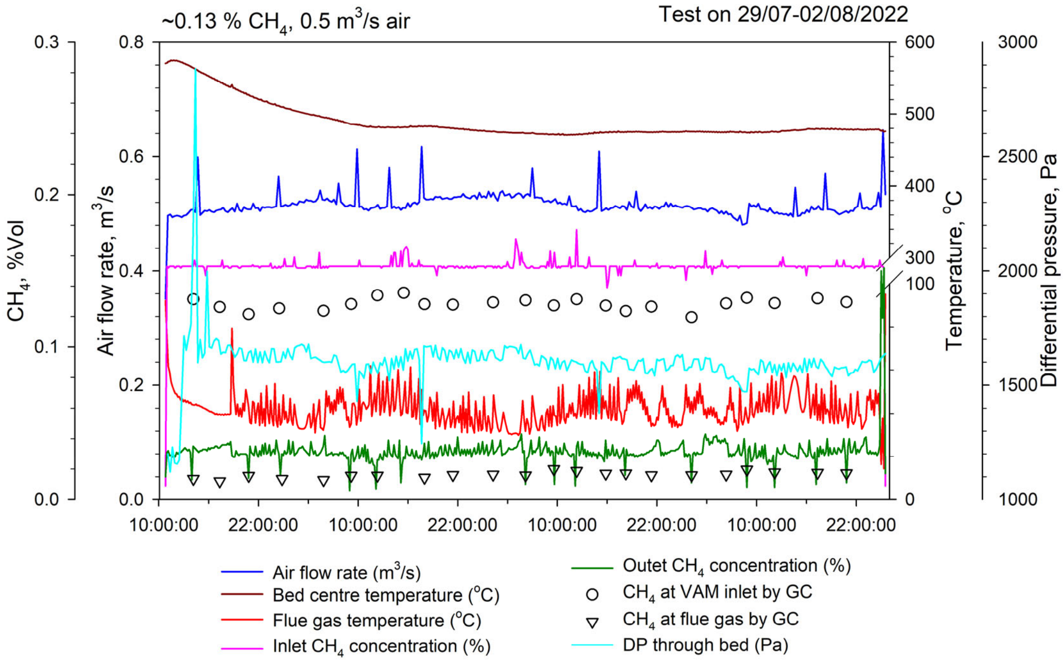

Figure 10 Results of site trial test #9 with 0.13 vol% VAM and 0.5 Nm^3/s VA.

4.10 Test #10: 0.13 vol% VAM and 0.33 Nm^3/s VA

The key findings are:

- The unit was tested for 45 hours with 0.13 vol% VAM and 0.33 Nm^3/s VA.
- Self-sustaining operation was not confirmed because the bed temperature slowly dropped during the testing period.
- The methane oxidation efficiency was 85-90%, similar to that achieved with 0.67 Nm^3/s flow rate, indicating that the current space velocity range was not a limiting factor for the unit.

Keeping the methane concentration at 0.13 vol%, the inlet VA flow rate was reduced from 0.5 to 0.33 Nm^3/s. The centre bed temperature decreased from about 600 to 500 °C in 42 hours (Figure 11). It seems that it did not reach an equilibrium state until the end of the test, although the methane oxidation efficiency was about 88 %. However, it was adequate for the purpose of investigating the effect of the VA flow rate on methane oxidation efficiency. It was likely that the operation of the unit could not be self-sustained, or a lower flue gas temperature might be needed to reach an equilibrium state. No firm conclusions can be made at this stage. It also implies that flow rate plays a role in determining the minimum methane concentration required for self-sustaining operation. For this test, relevant heat loss would be higher than that for the test at 0.5 Nm^3/s.

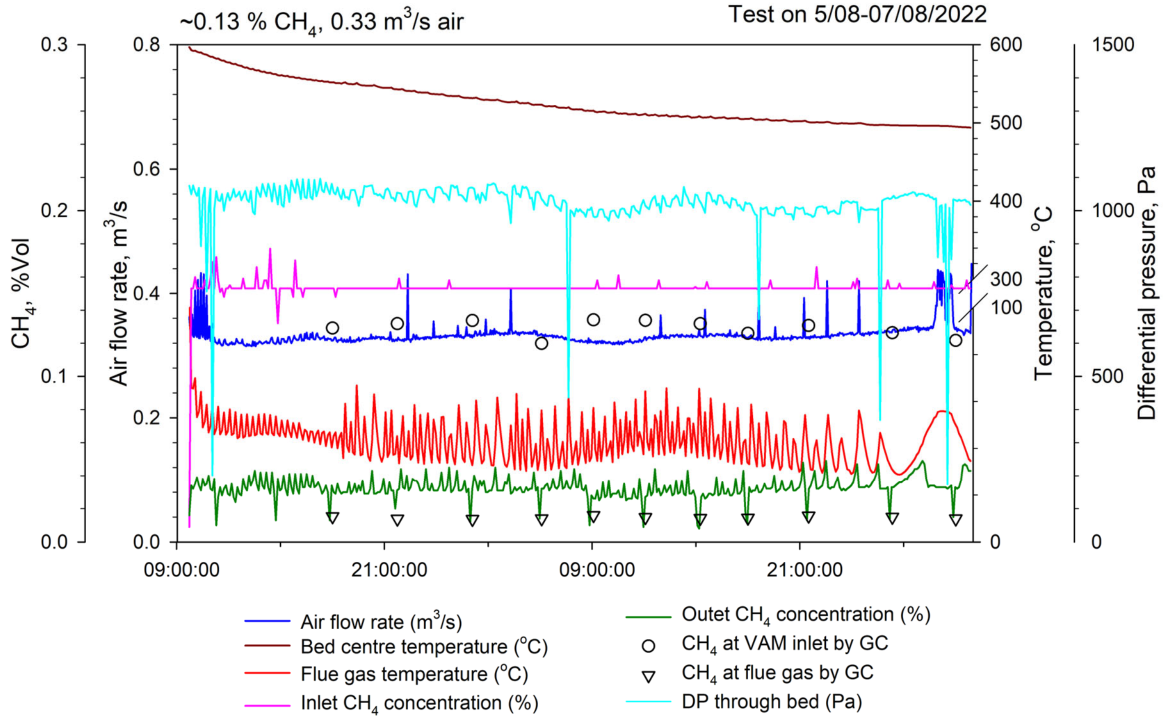

Figure 11 Results of site trial test #10 with 0.13 vol% VAM and 0.33 Nm^3/s VA.

4.11 Test #11: 0.13 vol% VAM and 0.67 Nm^3/s VA

The key findings are:

- The unit was tested for 58 hours with 0.13 vol% VAM and 0.67 Nm^3/VA, and the efficiency was 85-90%, comparable to that of Test #6.
- No evident degradation of catalyst performance was observed after a series of tests.

The inlet VA flow rate was again set to 0.67 Nm^3/s to examine the effect of the VA flow rate on both methane oxidation efficiency and the stability of the catalyst. The results are shown in Figure 12. The centre bed temperature was maintained at about 480 °C and the methane oxidation efficiency was in the range of 85-89% for 24 hours. As test #11 started immediately after test #10, the initial average bed temperature was about 500 °C whereas that of test #10 was about 600 °C. To compare with test #10, the average bed temperature was increased from 480 to over 550 °C by increasing the inlet VAM concentration from 0.13 vol% to 0.28 vol%. As a few hot spots of 700-800 °C with 0.28 vol% VAM were observed in 6 hours, the VAM concentration was reduced back to 0.13 vol%. The bed temperature was decreased to about 480 °C in 12 hours and maintained at the level for over 14 hours. The methane oxidation efficiency was about 85% at the end of the test. As the results are also comparable with test #6, the stability of the catalysts was confirmed to be very good. These results indicate that the catalytic VAMMIT unit may be able to accommodate some degree of fluctuation in VAM concentration with the auto-control mode of the flow switching time.

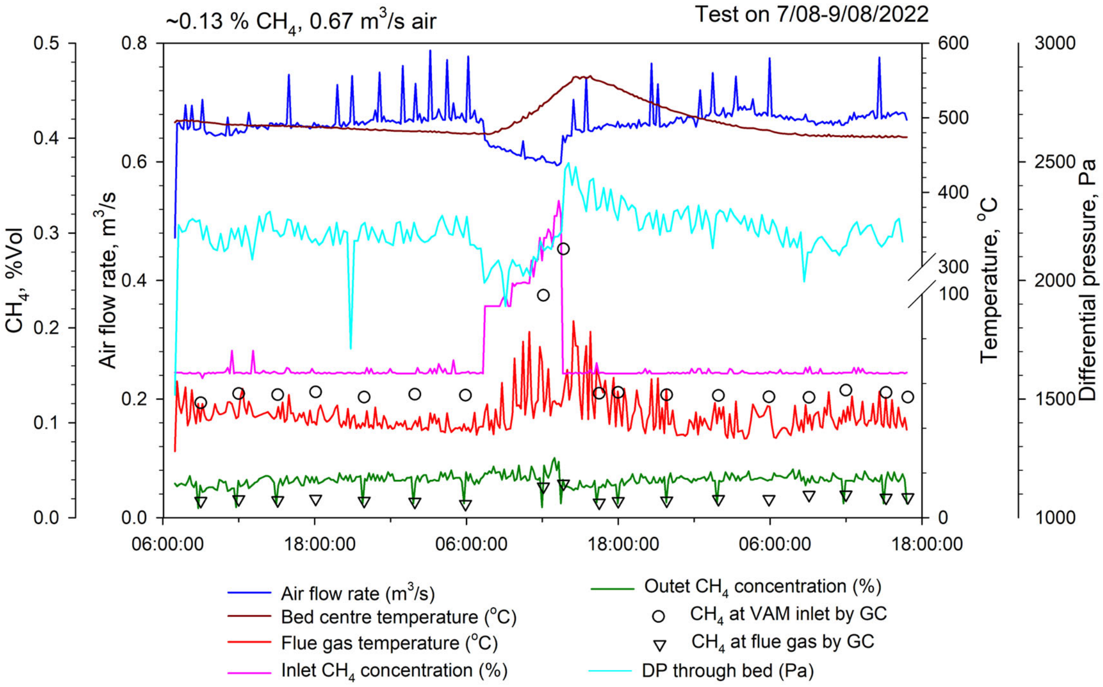

Figure 12 Results of site trial test #11 with 0.13 vol% VAM and 0.67 Nm^3/s VA.

4.12 Summary of site trials

Based on the hot trials conducted to date, the following key findings are summarised below:

- The pilot unit has been tested for a total of 476 hours, and it remains fully functional.
- The pilot unit can operate with concentrations as low as 0.1vol% VAM and a flow rate of 0.5 Nm^3/s, marking the first site demonstration of the CFRR technology for VAM abatement. The flow rate could be further increased to 0.67 Nm^3/s. However, processing VAM concentrations higher than 0.3vol% proved challenging because the bed structure was retrofitted from a thermal VAMMIT unit and was not optimised for CFRR operation. Optimisation of catalytic regenerative bed and process design is required for further development.
- Under manual control, catalytic VAMMIT operation was shown to be self-sustainable with a VAM concentration of 0.13 vol% and VA flow rates of 0.5 and 0.67 Nm^3/s. The methane oxidation efficiency remained unchanged (84%-90%) when the VA flow rate was increased from 0.5 to 0.67 Nm^3/s while maintaining a constant switching time of 120 s. However, it may not work with a VA flow rate of 0.33 Nm^3/s. The increase in VA flow rate did not have any adverse effects on methane oxidation efficiency, indicating that space velocity was not the limiting factor. It is possible that there are short circuit paths in the regenerative bed, where methane can pass through without oxidation. Hence, the methane oxidation efficiency remained within the range of 84-90%. Further investigation of the regenerative bed is needed after completing all trials.
- The catalytic VAMMIT unit is self-sustaining with 0.10-0.13 vol% VAM and 0.5 Nm^3/s and 0.67 Nm^3/s, aided by auto-control of the switching time reacting to changes in VAM vol%. The auto-control logic could be further optimised for operating the pilot unit with higher methane concentrations to prevent overheating. The auto-control logic utilises the bottom and down ceramic bed temperatures as control parameters, adjusting the switching time to achieve the desired temperature settings. The

regenerative beds, comprising both ceramic blocks and catalytic layers, could achieve a more stable temperature profile. Additionally, it is noted that the catalytic bed temperature (i.e., 440 °C in test #8) was lower when the VAM concentration was approximately 0.10-0.11 vol%, while it reached around 480 °C (test #9) when the VAM concentration was about 0.13 vol%. This difference can be attributed to the lower heat generation associated with lower VAM concentrations.

- The test conditions of test #8 were similar to those of test #4. However, the methane oxidation efficiency was lower in test #8 (77-88%) compared to test #4 (84-90%). This difference is likely due to the sampling error caused by the reduced switching time. Consequently, it is probable that the methane oxidation efficiency was not affected when the inlet methane concentration was decreased from 0.13 vol% (e.g., test #9) to 0.09-0.11 vol% (test #8). This suggests that the catalytic bed can be operated at temperature as low as 440 °C without compromising methane oxidation efficiency.
- The catalyst's performance remained stable during the test period. The methane oxidation efficiency did not decrease when the VA flow rate was increased to 0.67 Nm^3/s. The next step, therefore, is to modify the unit to increase the inlet VA flow rate to 2 Nm^3/s for further trials in order to determine the maximum space velocity limit.
- In general, manual control is not feasible as the system response time is too long, in particular when feed methane concentration is relatively high (e.g., > 0.3 vol%). A robust auto-control logic is required to process high methane concentrations if possible.

One major challenge was associated with heat management when operating the catalytic VAMMIT unit with higher VAM concentrations. For instance, when undiluted VAM (0.32-0.46 vol%, GC: 0.29-0.38 vol%) was introduced into the catalytic VAMMIT unit, the bed temperature increased constantly. Several hotspots with temperatures exceeding 800 °C in the catalyst layers during the hot trials were observed. This phenomenon was attributed to more heat being retained in the catalytic bed than being removed by the exhaust gas. Therefore, the optimisation of catalytic regenerative bed structure is required for the further development of catalytic VAMMIT.

Adjusting the flow switching time proved effective in achieving some degree of heat balance; however, this control requires careful manipulation and may lead to extinguishing the unit. Hence, when VAM concentrations exceed 0.3 vol%, it is necessary to employ heat extraction from the bed to stabilise the bed temperature. Otherwise, it is highly likely that the catalytic bed could revert to operation as a thermal bed over time in terms of bed temperature (i.e. >800 °C). This issue requires careful consideration as it will increase the complexity of the catalytic VAMMIT unit and add to capital and operating costs. Alternatively, a new process design can also be considered to improve heat balance management.

5 Modification of the pilot unit

5.1 Installation of an upgraded blower

In this project, the planned site trials were completed to evaluate the performance of the catalytic VAMMIT pilot unit with up to 0.67 Nm^3/s of VA which was the maximum flow the original blower can deliver to the reactor. The methane oxidation efficiency was found to be in the range of 84 - 90 % with 0.10 - 0.28 vol% VAM. The maximum achievable VA flow rate of the current blower was found to be 0.67 Nm^3/s due to the blower power limitation.

It would be necessary to investigate the VA treatment capacity of the current VAMMIT pilot unit. Accordingly, the project team decided to upgrade the blower and pipe work to deliver VA flow rates of up to 2.0 Nm^3/s for further tests. Also, as it was identified that the current DN150 piping between the SI and catalytic VAMMIT unit could give rise to more than 16 kPa of pressure loss, it was necessary to upgrade the current piping to DN300. Because such a modification was out of scope in the current project, the team obtained approval for the modification from CINSW.

From August to November 2022, the design of the current unit was modified and an upgrade was completed including:

- Mechanical drawings of DN300 piping connecting the new blower to the SI system
- Mechanical drawings of the new blower and its support
- Design of separate VSD panel enclosure (Figure 13) and electrical diagrams with verification and approval for construction
- Modification of the existing electrical diagrams to accommodate the new blower
- Modification of the existing Control and Monitoring system program

Figure 13 VSD Panel of a new blower and power supply from WestVAMP Plant.

After a lengthy process for site contractor validation, the mechanical and electrical installation and function tests for the new blower were completed in June 2023.

5.2 Commissioning and trials of the modified unit

Prior to commissioning the modified unit, an informal HAZOP Study for the new blower was carried out on 20th June. It was identified that testing of the start-up burner for ignition with a range of air flow rates was required. Once all the SI and catalytic VAMMIT unit sensors were calibrated, the ignition tests were carried out in July. Hot trials were carried out in August and September 2023 with various VA flow rates and VAM concentrations.

The results of these tests are not included in this report but will be presented in a supplementary report.

6 Preliminary life cycle assessment

6.1 Process configuration

The operating principles of a catalytic VAMMIT unit have previously been described in Chapter 2. Briefly, the VA is introduced from the safe ducting into the regenerative bed by a blower. VAM is then oxidised into CO_2 under the influence of the catalytic layers. Finally, the flue gas is released into the atmosphere. As methane oxidation is exothermic, the system can be operated in a self-sustaining manner over a range of VAM concentrations if appropriate heat management is deployed. The process is expected to be a significant advance in emission reduction capability as methane's 100-year global warming potential (GWP) is 28 times of that of CO_2.

The following main assumptions have been made for a full-scale catalytic VAMMIT unit:

1. The unit operates at constant VA flow rate
2. The operating bed temperature is constant, which is not affected by inlet VAM concentrations
3. A conservative pressure increase across the blower (7500 Pa) is assumed for the calculation of power consumption.

Table 4 summarises key process parameters for a full-scale catalytic VAMMIT unit with a VA flow rate of 17 m^2/s based on the results from this pilot-scale unit. VAM concentrations of 0.1-0.8 vol% and two CH_4 conversion rates (90% and 95%) were considered. These values were either from system design or calculated based on trial results. Although the current design is not able to process relatively high VAM concentrations, it might be achievable when an optimised design is used. For an LCA study, it is beneficial to investigate emissions reduction performance over a wide range of VAM concentrations.

Table 4 Summary of assumptions of process parameters of the catalytic VAMMIT unit

Parameters	Value	Source of data or comments
VA flow rate (m^3/s)	17	System design
VAM concentration (CH_4, vol%)	0.1-0.8	System design
CO_2 concentration in VA (vol%)	0.1	Based on trial results
LPG consumption (kg per start-up)	302.6	Based on trial results
Pressure increase across the blower (Pa)	7500	System design based on trial results
Overall efficiency of the blower	0.73	based on trial results
Electricity usage (kW)	174.9	Calculated from VA flow rate and pressure drop across the bed

6.2 Scope and assumptions for a life cycle assessment study

A life cycle assessment (LCA) study for a catalytic VAMMIT system was conducted according to the principles of ISO 14044 (2006) (omitting an external peer review element). This can be considered as a 'cradle to gate' streamlined greenhouse gas LCA study.

Material and energy balances were used to quantify the key process parameters (e.g., emissions, resource, and energy consumptions) associated with the process of mitigating methane emissions from VAM during the mining process through use of the VAMMIT system. The greenhouse gas emission-related environmental impacts of this process were then evaluated. The results were compared to a scenario in which the ventilation air methane is simply vented to atmosphere. The latter is a common practice in the coal industry. This comparison can be used to assist a decision maker on whether the technology is suitable and if it is a solution, by how much that can help to mitigate fugitive methane emissions.

The system boundary, defined as the allocation of the operations that are included in the LCA for the catalytic VAMMIT system, included the safe ducting system for the ventilation air output of the mine shaft, the catalytic VAMMIT system, and the energy and emissions related to the operation of both these systems.

The LCA methodology calculates performances per unit of product/activity, also called the functional unit. The activity of this study was venting the VAM, thus one kg CO_2 equivalent (kg CO_2-e) emitted per tonne of ventilation air vented was the functional unit for this study. Figure 14 illustrates the system boundary and functional units for the catalytic VAMMIT system. To assess the reduction in the carbon emissions in the ventilation air, the total emissions and energy consumption associated with this activity were analysed in a scenario in which the catalytic VAMMIT system is not present, and the ventilation air is not treated and simply vented to atmosphere.

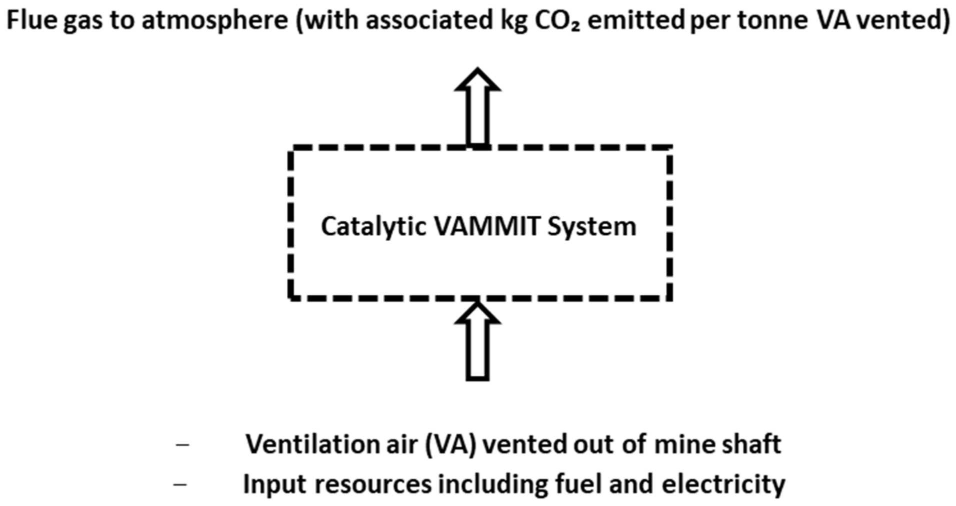

Figure 14 System boundary and functional unit for the VAMMIT system.

The following assumptions were made to undertake this LCA study:

1. The scenario that VA was vented to the atmosphere directly was used as the reference
2. The GWP of methane was 28 times of that of CO_2
3. The start-up burner was used four times a year (the Scope 1 emissions from start-up were negligible compared with those from electricity consumption)
4. The unit was operated on a basis of 24 hour per day and 300 day per year, the lifetime was 20 years
5. Four VAM concentration conditions were investigated (0.1, 0.3, 0.5 and 0.8 vol%)
6. The CO_2 concentration in the VA was 0.1 vol%
7. Two methane conversion efficiencies (i.e., 90 % and 95%) were studied
8. CO_2 was the only product of methane oxidation
9. The emissions for the manufacturing of the unit were excluded
10. The only electricity consumption was from the blower and other electricity usage from the instrument and control system was ignored.

The associated characterisation factors and data for estimating the Scope 1 and 2 emissions for the LPG (60.6 kg CO_2-e/GJ) and electricity usage (0.79 kg CO_2-e/kWh) by the catalytic VAMMIT system, respectively, can be found in the National Greenhouse Accounts Factors (DISER 2021).

6.3 Life cycle inventory data

As described above, the catalytic VAMMIT system is a catalytic flow reverse reactor that can oxidise methane into CO_2 with the assistance of catalyst. The flow of the VA from the mine duct to the reactor is driven by a blower. The life cycle inventory (LCI) data is shown in Table 5. It is noted that the electricity consumption from the blower accounted for most of the emissions from the catalytic VAMMIT system. The emissions of the blower were only determined by the VA flow rate as the pressure increase is constant. The emissions from LPG usage (i.e., start-up burner) were less than 0.1 % of the total emissions.

Table 5 The LCI data for the catalytic VAMMIT system (VA flow rate of 17 m^3/s)

Items	Value	Source of data or comments
VA mass flow rate	76971.6 kg/h	Calculated from VA flow rate of 17 m^3/s
LPG usage	0.1 kg CO_2-e/h	Estimated from trial results
Blower	138.17 kg CO_2-e/h	Electricity required

6.4 Greenhouse gas emissions

The greenhouse gas emissions from the ventilation air (VA) are from both methane and CO_2. The CO_2-e emissions from the catalytic VAMMIT unit are from:

1. CO_2 in the feed VA.
2. Unreacted methane in the flue gas; this is quantified by the methane conversion efficiency and VAM concentration in the feed VA. Two scenarios (90% and 95%) were used in this LCA study.
3. CO_2 in the flue gas from methane oxidation.
4. CO_2 emissions from the operation of the catalytic VAMMIT system and the emissions are from the electricity consumption of the blower and the LPG usage for the start-up burner. The electricity consumption of the blower accounts for >99.5% of CO_2 emissions from the system.

Figure 15 compares the CO_2-e emissions under three different scenarios with a VA processing flow rate of 17 Nm^3/s. In general, the deployment of the catalytic VAMMIT system can significantly reduce the greenhouse gas emissions. The Scope 1 emissions from the LPG usage were negligible (0.006 kg/t VA, not shown in Figure 15), assuming four start-ups and 300-day operation per year. The Scope 2 emissions from the electricity usage of the blower were nearly constant at 1.8 kg/t VA, as the usage was primarily proportional to the VA flow rate when assuming a constant pressure increase (i.e., 7500 Pa as shown in Table 4). This contribution could be smaller for the honeycomb monolithic bed structure. In the pilot unit, it was measured at about 2300 Pa when the flow rate was 0.67 m^3/s. For 0.1 vol% VAM, the CO_2-e emissions were 17.4, 6.3 and 5.6 kg per tonne of VA vented for three scenarios: no treatment, 90% conversion and 95% conversion, corresponding to reduction rates of 63.8% and 67.6%. In particular, the emissions contribution from the blower accounted for 28% and 32% of the total emissions at 90% and 95% conversion, respectively, underscoring the importance of minimising unit power consumption. The emission reductions were more significant when the VAM concentration was higher, while maintaining the same methane oxidation efficiency.

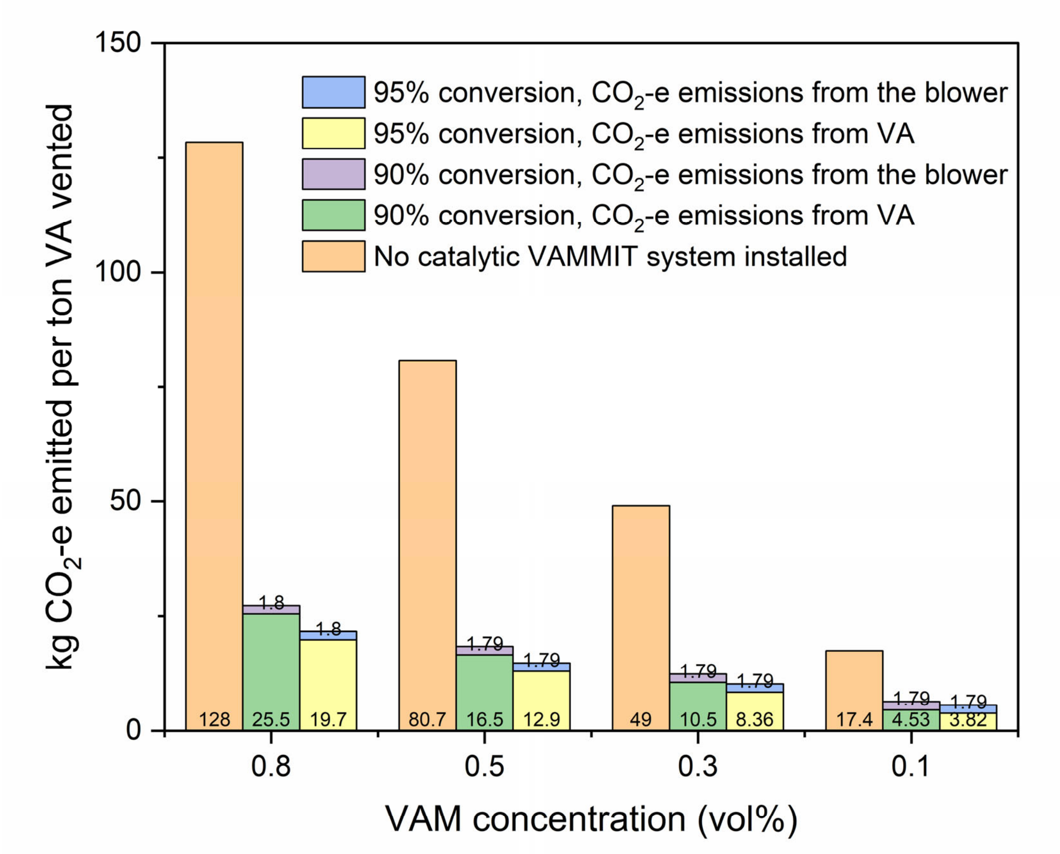

Figure 15 Comparison of CO_2 emissions from VA under three different scenarios (VA flow rate of 17 m^3/s).

7 Conclusions and recommendations

7.1 Conclusions

A novel pilot-scale catalytic VAMMIT unit was successfully constructed by retrofitting an existing thermal version VAMMIT unit at Appin coal mine. The regenerative bed was redesigned and constructed using catalytic bedding materials. The reactor bed consisted of ceramic and catalyst monolithic blocks. Design calculations were carried out based on both our previous catalyst performance data from a catalytic combustor and recent lab-scale testing results. All catalysts used were commercially available and Pd-based, fabricated using washcoating technology.

Eight commercial honeycomb monolithic Pd/Al_2O_3 catalysts were tested with simulated ventilation air streams using a lab testing rig and the best performance catalysts were selected.

In addition to the catalytic bed, new snorkel ducts were also designed, procured, and installed since the original duct could not be used at the mine site. All mechanical designs were verified by a third party to meet Australian standards prior to construction. All modifications to the previous thermal VAMMIT unit and site infrastructure (SI) were completed by the end of 2019.

After commissioning and relevant maintenance, the catalytic VAMMIT unit was fully functional, and it was successfully operated for 476 hours without any significant degradation in methane oxidation efficiency. The tests indicated that the catalyst had good stability under real VA conditions. The unit was tested under various VAM concentrations (0.08-0.38 vol%) and three VA flow rates (0.33, 0.5, and 0.67 Nm^3/s). The unit can maintain sustainable operation with VAM concentrations as low as 0.1 vol% at a flow rate of 0.5 m^3/s. Using manual control of the flow switching time, the catalytic VAMMIT unit could be self-sustained with a VAM concentration of 0.13 vol% and VA flow rates of 0.5 and 0.67 Nm^3/s, respectively. The methane oxidation efficiency ranged from 84% to 90%. However, it may not work with a VA flow rate of 0.33 Nm^3/s. Processing high VAM concentrations (e.g. >0.3 vol%) presented a challenge for the unit as the bed temperature increased rapidly, with some hotspots exceeding the catalyst's operating temperature of 800 °C, suggesting an optimised bed design is needed.

With the deployment of the auto-control of the switching time, the catalytic VAMMIT unit could be self-sustained with VAM concentrations ranging from about 0.10 to 0.13 vol% and a VA flow rate of 0.5 and 0.67 Nm^3/s. When the inlet VA flow rate was fixed at 0.5 Nm^3/s, the catalytic bed temperature was influenced by the inlet VAM concentration, decreasing from 480 °C with 0.13 vol% VAM to 440 °C with about 0.10 vol% VAM, while the methane oxidation efficiency remained nearly unchanged.

This has been the first on-site demonstration of a CFRR capable of processing 0.1 vol% VAM, which is significantly lower than the minimum VAM concentration required by TFRRs (e.g. 0.3 vol%), supplied by MEGTEC, Dürr, VAMOX^{TM} and Shengdong. Processing lower VAM concentrations is possible because CFRR can be operated at a much lower temperatures compared to TFRR. This provides a technical solution for mine sites with low VAM concentrations.

It is noted that the oxidation efficiency of the pilot unit (80-90%) was lower than that of TFRR (i.e. >95%), even though the catalyst showed nearly 100% efficiency under lab conditions. This discrepancy may be attributed to variations of catalyst activity of supplied catalyst blocks, but it is more likely a result of limiting factors arising from the engineering design (e.g., uneven flow distribution, mismatch of heat transfer between the ceramic blocks and catalyst blocks) and structural failures in the bed, such as block collapses. Nevertheless, it is expected that higher oxidation efficiency and higher space velocity can be achieved by optimising the catalytic bed structure.

A study of LCA shows that the deployment of the catalytic VAMMIT system (i.e., 17 Nm^3/s VA) can significantly reduce greenhouse gas emissions. The Scope 1 emissions from LPG usage were negligible, while the Scope 2 emissions from the electricity usage of the blower remained constant at 1.8 kg/t VA. For 0.1 vol% VAM, the CO_2-e emissions were 17.4, 6.3 and 5.6 kg per tonne of VA vented for three scenarios (i.e., no treatment, 90% and 95% conversion). Among them, the emissions contribution from the blower accounted for 28% and 32% of the total emissions at 90% and 95% conversion, respectively. The emission reductions were more significant when the VAM concentration was higher, while maintaining the same methane oxidation efficiency.

As the catalyst remained stable throughout the entire testing period, the project team made the decision to advance to the next phase, which involves operating the catalytic VAMMIT unit at higher flow rates, potentially reaching up to 2 Nm^3/s. For this purpose, a new blower and VSD were installed, and the inlet pipe (DN150) was replaced with a DN300 pipe. Further site trials were conducted in August and September 2023 and will be described separately in a supplementary report.

7.2 Recommendations

Based on the results of the catalytic VAMMIT unit trials, the following recommendations are put forward:

- Optimisation of the regenerative catalytic bed: It was found that heat management was challenging when the VAM concentration was high (>0.3 vol%). Since the catalytic VAMMIT was developed based on an existing thermal version, the overall bed height was fixed, limiting its heat management ability. It is not optimal for the catalytic process. Thus, it is highly recommended to design a purpose-built bed specifically for catalytic operation, that can further improve the performance of the catalytic VAMMIT system.
- Robust control logic for heat management: Heat management is crucial as the catalysts can only operate within a specific temperature range. Controlling the heat balance of the reactor through variation of flow switching time can partially address this issue. However, robust control logic considering the overall heat balance and heat transfer of the system is critical for achieving stable operation across a wide range of VAM concentrations.
- Full-scale demonstration: Conducting a full-scale demonstration is essential to evaluate the overall performance of the catalytic VAMMIT technology, providing that an appropriate design process is conducted. This will provide valuable insights for the commercialisation of the technology.
- Long-term operational performance: Dust deposition can significantly degrade system performance by covering active catalytic sites, thereby reducing oxidation efficiency and increasing pressure drop, resulting in higher power consumption. Longer term operation of the system will be required to examine and understand the long-term effects of rock dust build up on catalyst surfaces.
- Development of cost-effective, high-performance catalysts: Pd-based catalysts were used in the project due to their superior performance. However, they were also expensive. It is highly desirable to develop low-cost catalysts, as this would significantly reduce the capital cost for the large-scale deployment of catalytic VAMMIT technology.

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SIGN OFF

I, the undersigned, being a person duly authorised by the Grantee, certify that:

(a) the above information is true and complete;
(b) the expenditure of the Funding received to date has been used solely on the Project; and
(c) there is no matter or circumstances of which I am aware that would constitute a breach by the Grantee or, if applicable by the End Recipient and Subcontractors', of any term of the Funding Deed.

Signature:

Position: Mineral Resources Research Director

Name: Dr Hua Guo

Date: 8th March 2024