VENTILATION AIR METHANE (VAM)

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Ventilation Air Methane

- Ventilation Air Methane (VAM) refers to the methane gas found in the ventilation systems of underground coal mines. Methane is a by-product of coal mining and is often released into the air as a result of natural processes, including the excavation of coal.
- VAM is typically diluted with air and is considered to be a low-concentration form of methane, which can be difficult to capture and manage.
- Because methane is a potent greenhouse gas, it is released into the atmosphere and is a significant concern for environmental and climate issues. The challenge with VAM is that it is often present in low concentrations, which makes it difficult to capture and use as an energy source.

- VAM, the dilute methane emitted from mine ventilation shafts, is now recognized as an unused source of energy. A host of recently introduced technologies can reduce VAM emissions while harnessing thermal energy and can offer significant benefits to the world community.
- In India, the percentage of methane in VAM is less than 0.02% in most underground coal mines.
- There are a few underground coal mines wherein the percentage of methane ranges from 0.2 to 0.4% in ventilation air, and these mines may be suitable for a CDM Project.

- Though the concentration of methane in ventilation air is very low, the quantity of methane emitted into the environment from each underground mine is enormous. Methane of such low concentration is continuously emitted to the environment, increasing the GHG effect.

- If this low-concentration high volume methane emitted from the mine can be extracted from the ventilation air and the concentration is enriched through processes like chemical looping, a large quantity of high-concentration methane can be effectively utilised for power generation.

- Such a study is essential to evolve suitable technology for capturing the methane in ventilation air and not allowing it to go into the atmosphere, increasing the GHG effect.

- Capturing and utilizing VAM rather than venting was a challenging task, but new technologies have recently been developed and deployed to oxidize methane in ventilation air. In a highly gassy mine, VAM may be supplementary fuel. There are some underground coal mines in India that produce high-quality VAM, and the estimated CMM resource potential in these mines are presented in Table 1.

Table 1. Underground coal mines suitable for CMM production [3]

Sr. No.	Name of colliery & Coalfields	Degree of gassiness	CMM resource (in BCM)
1.	Amlabad colliery, Jharia coalfields	III	0.76
2.	Murulidih colliery, Jharia coalfields	III	4.98
3.	Central Purbatpur, Jharia coalfields	III	5.31
4.	Sudamdih colliery Jharia coalfields	III	0.86
5.	Kalidaspur colliery, Raniganj coalfields	III	3.78
6.	Ghusick colliery, Raniganj Coalfields	III	2.58

Utilization of VAM in these mines would provide opportunity to earn carbon credit by selling certified emission reduction (CER) through a CDM project and it would be helpful to reduce methane concentration in the atmosphere.

Methane Emission in the Atmosphere

- Generally, Indian coal mines are of low gassiness and concentration of methane in mine workings is maintained below prescribed percent by diluting emitted methane with ventilation air. The methane content in ventilation air of degree I and II gassy coal mines is generally too low.
- The first estimate of methane emission from Indian coal mining and handling activities was prepared using DGMS classification of degree of gassiness of coal seams as emission factors and estimated methane emission in the atmosphere was 0.4Tg for the year 1990.

A trend has been established on the basis of methane emission estimates for the years 1980 to 2000 with assumption that the coal production in the next 6 years would follow a linear trend and is shown in Figure 1.

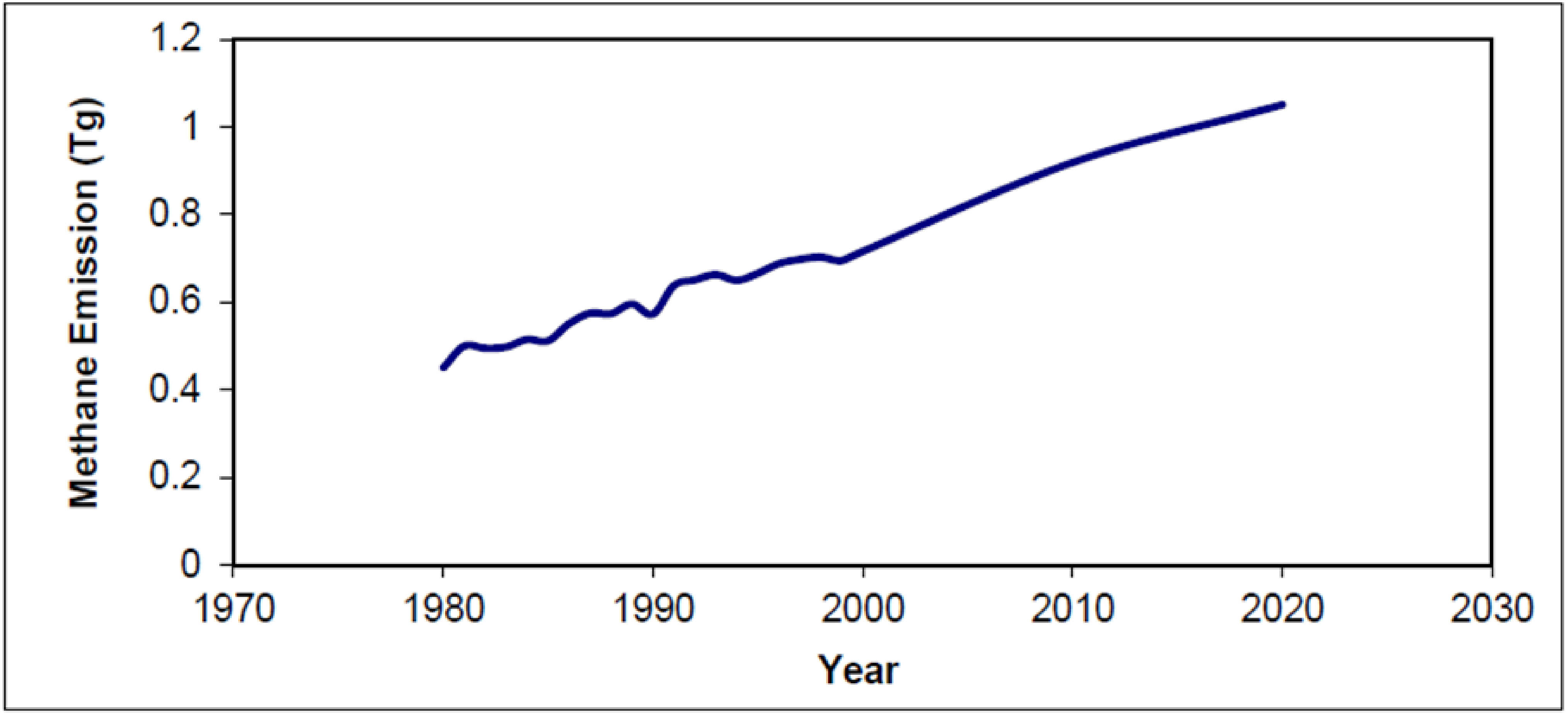


Fig.1. Trend of methane emission from coal mining and handling activities with projected value up to 2020 [6]

Gas Chromatography using Flame Ionization Detector (FID) was used to measure methane content, even it is low. Measurements were made in 16 surface and 83 underground mines of different degrees of gassiness to reduce uncertainty in emission factors. Estimates for methane emission to the atmosphere from coal mining activities were prepared for the year 2010 by using new emission factors developed by CIMFR, Dhanbad and estimates have been presented in the Table-2.

The methane emission into the atmosphere from Indian coal mining and handling activities has been estimated 0.77Tg for the year 2010.

Table 2. Methane emission in the atmosphere from coal mining and handling activities for the year 2010

Type of mines	Deg. of gassiness	Coal Production (million t)	Emission factors (m^3/t)	Methane emission (Tg)
Underground mines (Mining)	I	55.32	2.91	0.11
	II	13.82	13.08	0.12
	III	0.86	23.64	0.01
(Post mining)	I	55.32	0.98	0.04
	II	13.82	2.15	0.02
	III	0.85	3.12	0.00
		Surface mines		
(mining)	I	531.88	1.18	0.42
(Post-mining)	I	531.88	0.15	0.05
Total emission (Tg)				0.77

Challenges to Utilization of Ventilation Air Methane

- Utilization of VAM is the best method to reduce methane load in the atmosphere but it is challenging task from technical and economic point of view.
- Major challenges are **low and variable methane concentration, variable flow rates of ventilation air, changing location of working faces, impact on mining operations, and large and costly air handling system**. Other challenges can be government policies, technological issues and financial.
- Main challenges in India are **low coal production, lean methane in ventilation air, limited numbers of degree III gassy coal seams, no proper inventory and assessment of VAM resources potential in all degree III gassy mines, lack of gas pipe line infrastructure nearby coal fields and unclear of carbon credits**.

- To overcome the above challenges, steps to be adopted for methane reduction in the atmosphere are policy to curb methane volume release mine wise per year, mandatory policy for pre-mining degasification in high gassy coal mines, transparent dissemination of information for evaluating commercial viability, expediting private participation, market creation for clean energy technology, reliable cost recovery mechanism, support by government subsidies/incentives and adopting technology to a smaller scale that to suit Indian conditions.
- Investigation on quantification of ventilation air methane has been carried out in Moonidih and Sudamdih mines in Jharia coalfields to assess the potential for use of any of the VAM utilization technologies. A maximum of 0.2% methane concentration in ventilation air of Moonidih u/g mine was observed at 510TPD and 0.04% was determined for Sudamdih mine at 150TPD. Low rates of coal production from gassy mines are main constraint for utilization of ventilation air methane in India.

However, VAM can also be harnessed in some cases to generate energy. Technologies have been developed to capture and utilize VAM, including:

1. **Methane Destruction**: This involves technologies like catalytic combustion or thermal oxidation, which reduce methane emissions by converting them into carbon dioxide and water.
2. **Energy Recovery**: VAM can be captured and used to produce electricity through gas turbines or other energy recovery systems.

Using VAM for energy recovery helps reduce methane emissions, which contributes to mitigating the environmental impact of coal mining.

Ventilation Air Methane (VAM) mitigation and utilisation

- Mitigating and utilizing **Ventilation Air Methane (VAM)** is an important environmental and technological challenge in the mining industry. VAM is a potent greenhouse gas, and its release into the atmosphere contributes significantly to global warming. Mitigating and utilizing VAM not only helps reduce harmful emissions but can also provide energy recovery opportunities.
- Reducing methane emissions can yield significant benefits in the race to mitigate global temperature rise. The urgency of tackling methane emissions is highlighted in the Paris Agreement, which seeks to limit global temperature rise to well below 2°C above pre-industrial levels.

- Looking at its significant global warming potential, reducing methane emissions is recognized as one of the most effective strategies for achieving short-term climate objectives, making it a key focus in global efforts to combat climate change.

- While Indian underground coal mines emit significant amounts of methane, there is limited research on quantifying VAM emissions and exploring feasible utilization technologies. A comprehensive evaluation is needed to develop practical solutions for methane recovery and utilization in Indian mining conditions. This will provide a foundation for methane management in Indian underground coal mines, supporting national sustainability goals and global climate commitments.

TEMPERATURE-SWING ADSORPTION UNIT

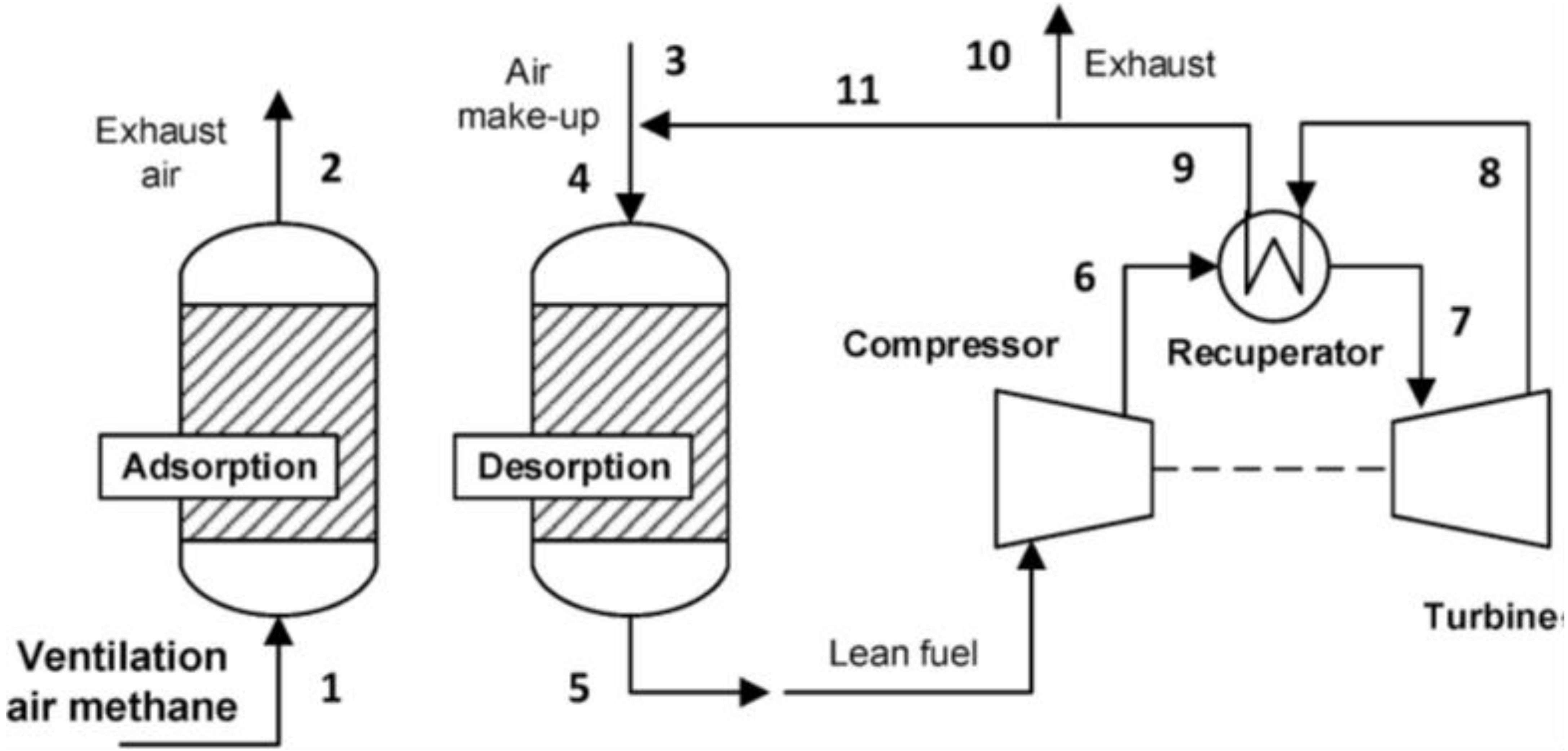
- Methane concentration can be achieved by fixed bed adsorption. This is one of the major promising technologies for methane concentration, providing good yields and adequate concentrations for the operation of the gas turbine .
- Temperature-swing adsorption (TSA) is the most economically feasible, given the lower energy requirements, and also the adsorption technique recommended for concentrations lower than 2%.
- One of the key parameters in TSA processes is the proper selection of the adsorbent material. There are two types of adsorbents: **metal-organic frameworks (MOFs) and activated carbons.**
- MOFs are known for its exceptional storage capacity for methane gas. Active carbons have lower adsorption capacity and selectivity. However, they are major competitors because of their lower cost.

- Another important parameter is the desorption temperature, **related to the energy required to recover the methane concentrated stream from the adsorbent.**

- Additionally, the energy required for the desorption step could be obtained from the effluent of the gas turbine.

Harnessing VAM using a fixed-bed temperature-swing adsorption unit

- The harnessing of coal mine ventilation air methane (VAM) emissions has been proposed according to a two-step integrated process: methane concentration in an adsorption/desorption unit, followed by methane combustion in a lean-burn gas turbine. The flowsheet of this process is depicted in Fig. 1.



- The concentration step is carried out in a fixed bed temperature-swing adsorption (TSA) operation. This unit is inherently discontinuous, with adsorption happening in a first step and, once the adsorbent is saturated, methane is recovered by desorption at a higher temperature. The concentration step must increase methane concentration to a minimum of 1%, in order to use a lean-burn gas turbine for the combustion.
- The lean-burn gas turbine is made of three elements: compressor, recuperator and turbine. The turbine is able of generating net work and, hence, produce electricity. The recuperator is used to pre-heat the feed before the combustion using the part of the energy of the combustion gases. In addition, part of these combustion gases can be used as the drag stream of the desorption process as shown in Fig. 1.

VAM Mitigation

1. Methane Capture and Destruction Technologies:

- **Catalytic Combustion:** This method involves using a catalyst to oxidize methane into less harmful substances like carbon dioxide and water at lower temperatures. It is considered a more energy-efficient approach than traditional combustion.
- **Thermal Oxidation (or Flare Systems):** In this method, methane is burned at high temperatures in a controlled environment, converting it into carbon dioxide and water vapor. The heat from this process can be used for energy production, though it has less efficiency compared to catalytic combustion.
- **Plasma Arc Technology:** This involves using high-temperature plasma arcs to break down methane into its basic components (hydrogen and carbon), which can then be further utilized or stored.
- **Biological Methane Oxidation (Biofilters):** Some innovative approaches use biological processes to oxidize methane. In this case, methane is passed through a bioreactor or biofilter, where microbes naturally consume the methane and convert it into non-harmful byproducts. This is more commonly used in scenarios with very low methane concentrations and is being explored as a potential mitigation and utilization strategy for VAM.

2. Coal Mine Methane (CMM) Pre-mining Capture:

- **Pre-mining Gas Drainage:** Prior to mining, methane can be extracted from coal seams to prevent the release of gas during mining operations. This is typically done by drilling wells into coal seams and extracting the gas.
- **Underground Draining:** After mining begins, methane can still be extracted through the mine's ventilation system by drilling additional wells to intercept the gas before it can reach the ventilation air.

VAM Utilization

- Utilizing VAM for energy recovery is a promising option, though it comes with its own set of challenges. The low concentration of methane in ventilation air makes energy recovery more complex, but technologies are emerging to make this process more viable.
- **Different processes such as cryogenic, pressure swing adsorption, solvent absorption, molecular gate, and membrane technologies are used for concentrating the methane in mine ventilation air When the methane is concentrated to 30% or higher, a conventional gas turbine can be employed to generate electricity.**
- **Energy Recovery via Gas Turbines:**
  - VAM can be fed into a gas turbine, where it is combusted to produce electricity. However, because VAM concentrations are low, it often needs to be mixed with other fuels or concentrated before it can be used effectively in a turbine. This method has been successfully demonstrated in some pilot projects. gas turbines typically cannot utilize CMM below 50% methane and require the gas to be compressed prior to use
- **Microturbines:**
  - Microturbines are smaller versions of gas turbines that can generate power from low-concentration methane like VAM. These turbines are more suitable for situations where methane concentration is not high enough to fuel large turbines. Microturbines can convert methane into electricity, providing a useful source of power for the mine.
- **Reciprocating Engines:**
  - Reciprocating internal combustion engines have been used to convert methane into electrical energy. Like gas turbines, these engines require higher methane concentrations, but technological advancements have made it easier to use low-concentration methane for energy production.

- **Utilization for Chemical Production:**
  - Some emerging technologies focus on converting methane into useful chemicals, like methanol or hydrogen. For instance, methane can be converted into syngas (a mixture of hydrogen and carbon monoxide), which can then be further processed into fuels or chemicals. This process is still in development, but it could offer an alternative means to convert VAM into something valuable.
- **Carbon Capture and Storage (CCS):**
  - While not directly a method of utilizing methane, CCS can play a role in the mitigation of methane by capturing CO2 from the combustion process of VAM and storing it underground. This can reduce the overall greenhouse gas impact of burning methane for energy recovery.

Ventilation Air Methane Utilization Technologies

- Utilization technologies of ventilation air methane based on thermal oxidation or catalytic oxidation principles are used to produce heat for the generation of useful energy. The combustion process of methane and heat generated are presented by the following chemical reaction:

$$CH4 + O2 = CO2 + 2H20, \Delta H = -802.7 kJ/ mol.$$

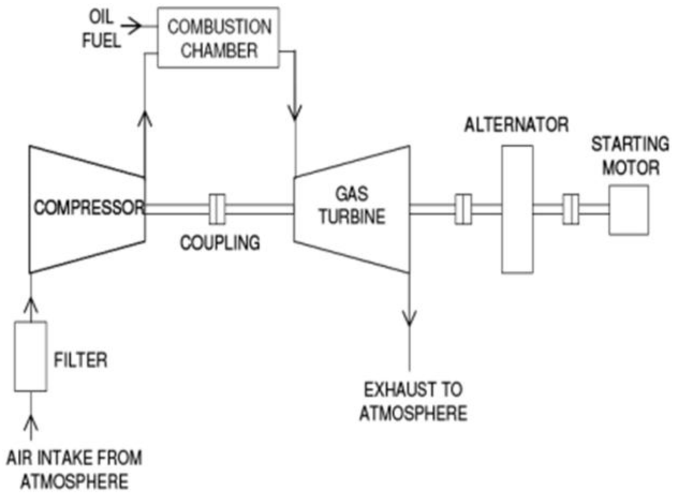
- The technologies for utilization of VAM are classified into three categories viz. **Ancillary use, Principal use and other technologies depending on the concentration of methane and combustion systems.**
- In the Ancillary use technologies, the VAM is used as supplementary fuel in **gas turbine, internal combustion engines and coal fired power station**. In the combustion system, oxygen of ambient air combines with the primary fuel to generate energy.

Challenges in VAM Mitigation and Utilization

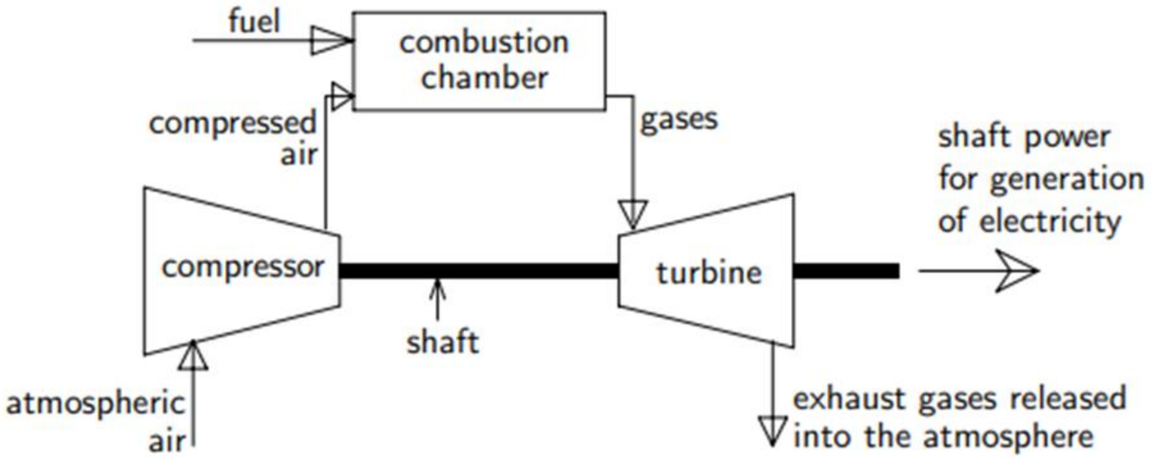
- **Low Methane Concentration:** One of the primary challenges of VAM utilization is the low concentration of methane (typically 0.3% to 1%), which makes it harder to use efficiently in energy recovery systems.
- **Cost of Technology:** Technologies for capturing and utilizing VAM are still relatively expensive, especially in underground mining environments. The costs of installation, operation, and maintenance of methane recovery and destruction systems can be high.
- **Mine-Specific Variability:** Each mine has unique characteristics (size, methane content, ventilation system design) that influence how VAM can be captured and utilized. This variability means that there isn't a one-size-fits-all solution.
- **Energy Efficiency:** While utilizing VAM for energy recovery is possible, the process is often not as energy-efficient as other more traditional methods of energy generation, which may require additional infrastructure and optimization.

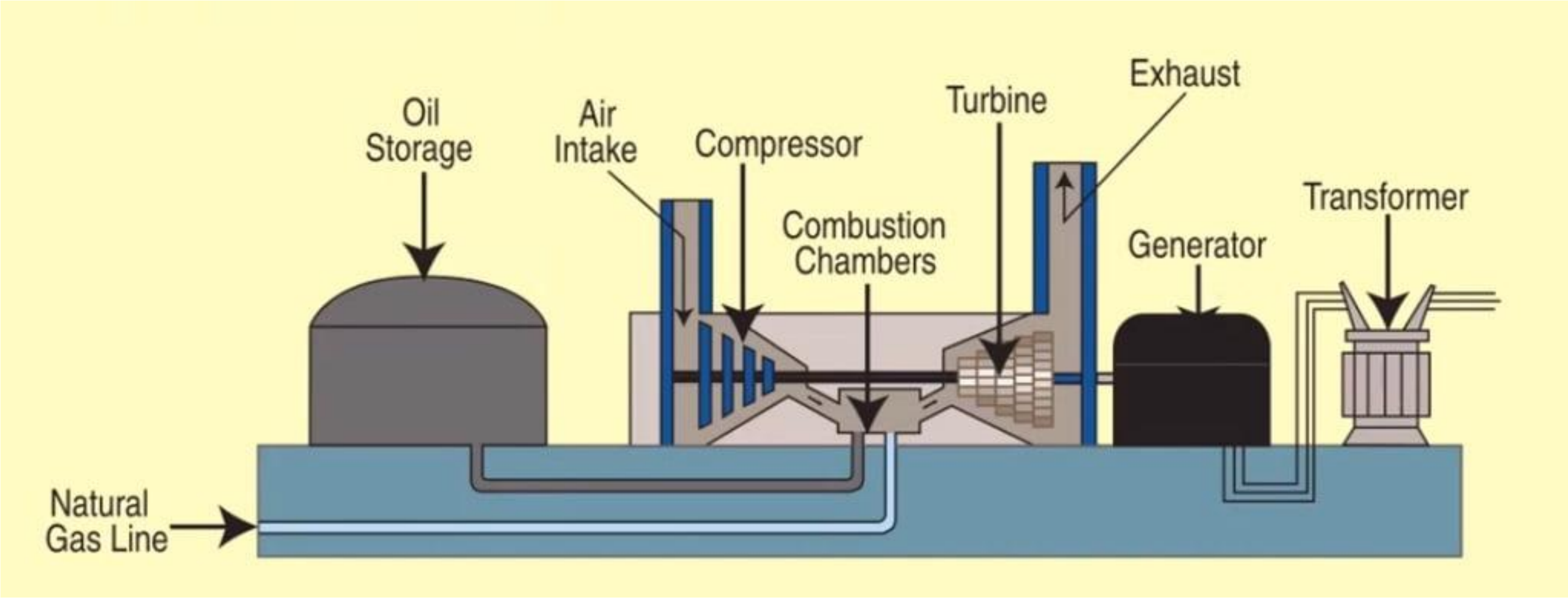
Conclusion

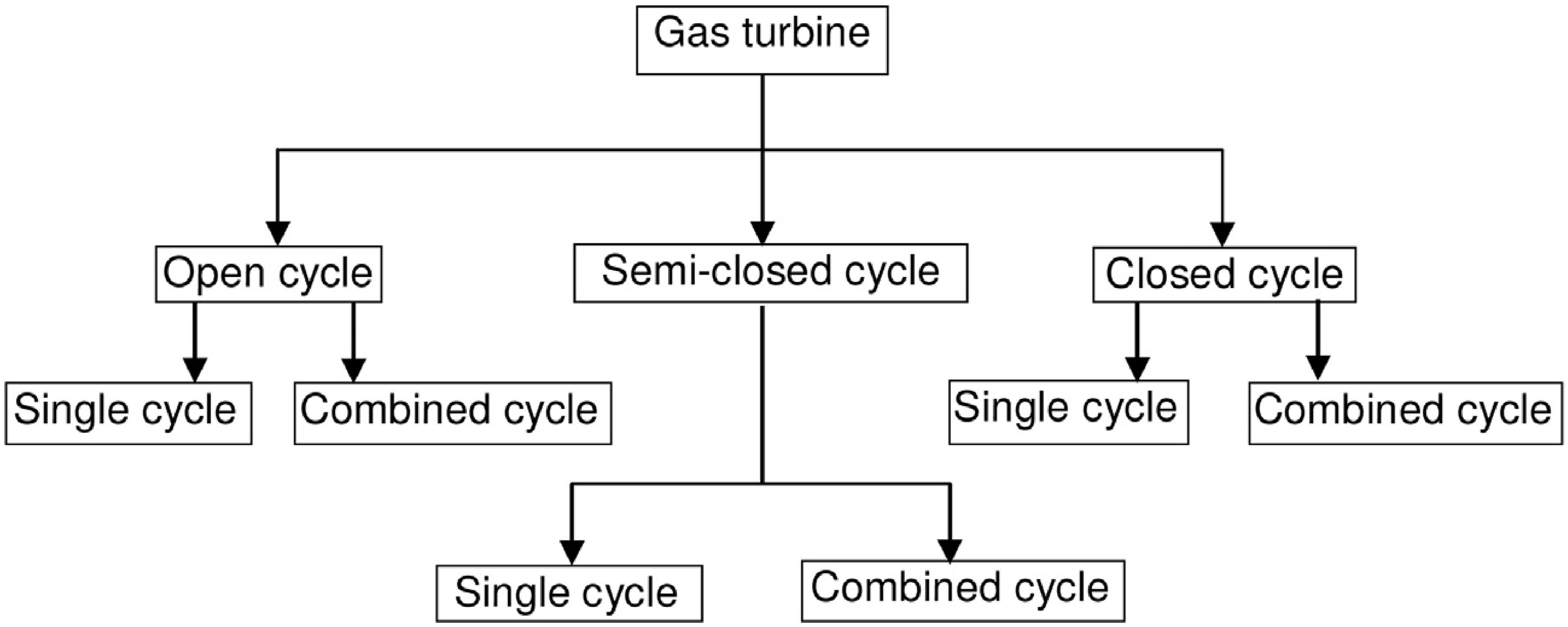
Mitigating and utilizing VAM represents a significant opportunity for reducing methane emissions from mining activities and generating usable energy. While technologies for VAM mitigation and utilization continue to improve, challenges remain related to efficiency, costs, and mine-specific factors. As global pressures to reduce greenhouse gas emissions increase, investing in and scaling up VAM mitigation and utilization strategies will be essential to achieving environmental sustainability in the mining industry.

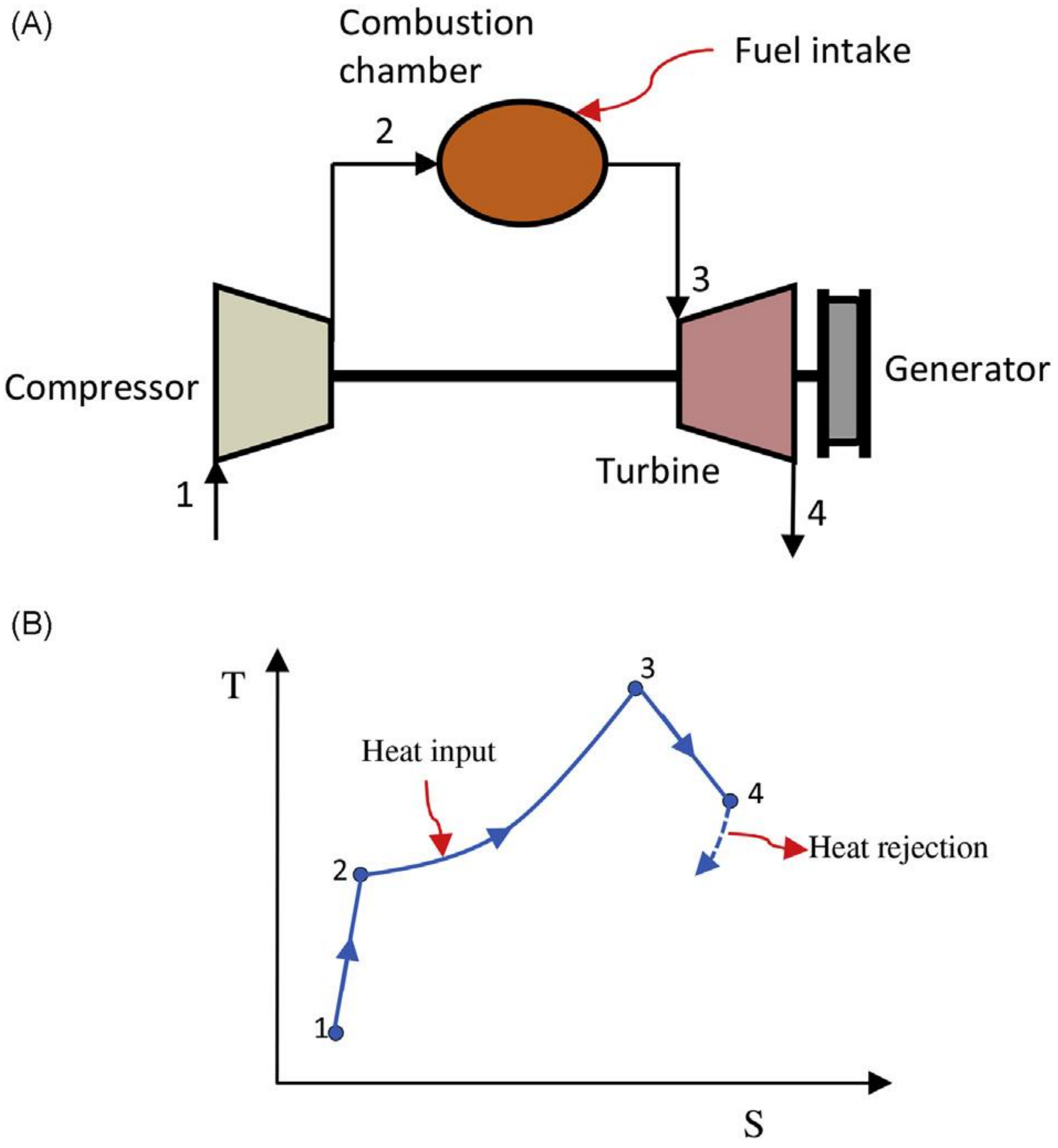


Schematic diagram of a Simple Gas Turbine Power plant

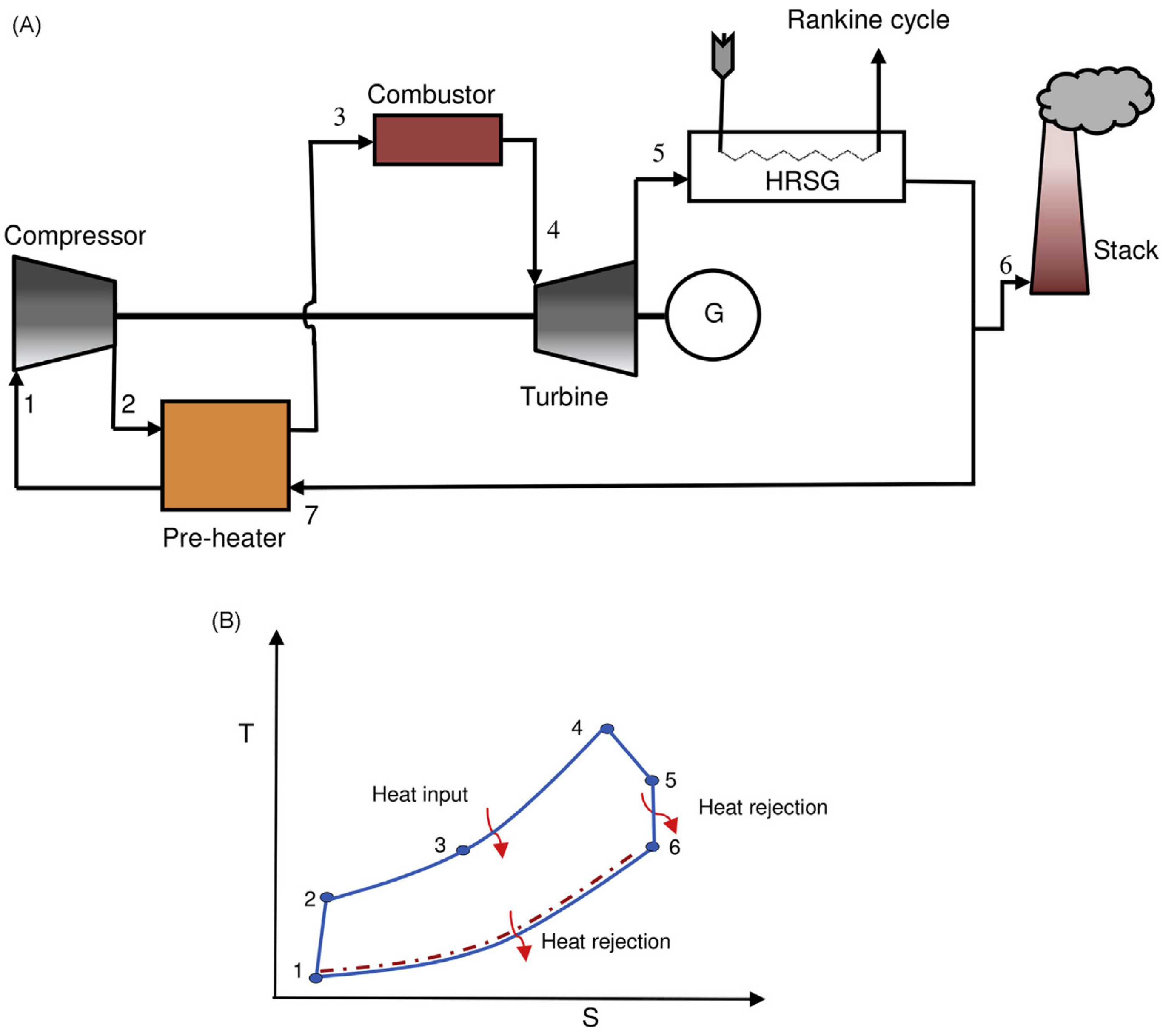




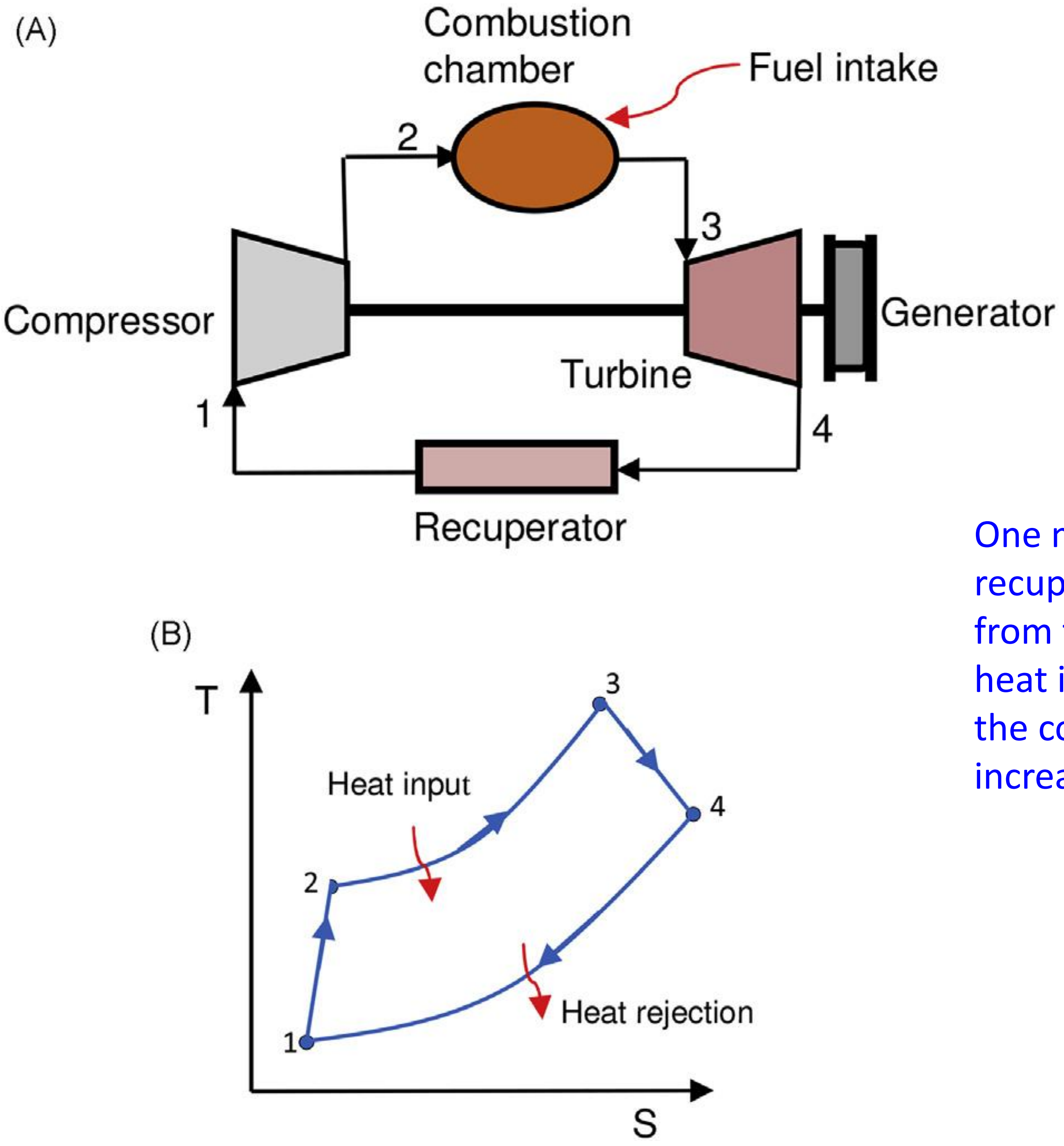

Gas turbine
Open cycle
Semi-closed cycle
Closed cycle
Single cycle
Combined cycle
Single cycle
Combined cycle
Single cycle
Combined cycle



Open cycle gas turbine: (A) Schematic representation of system and (B) T–S diagram.

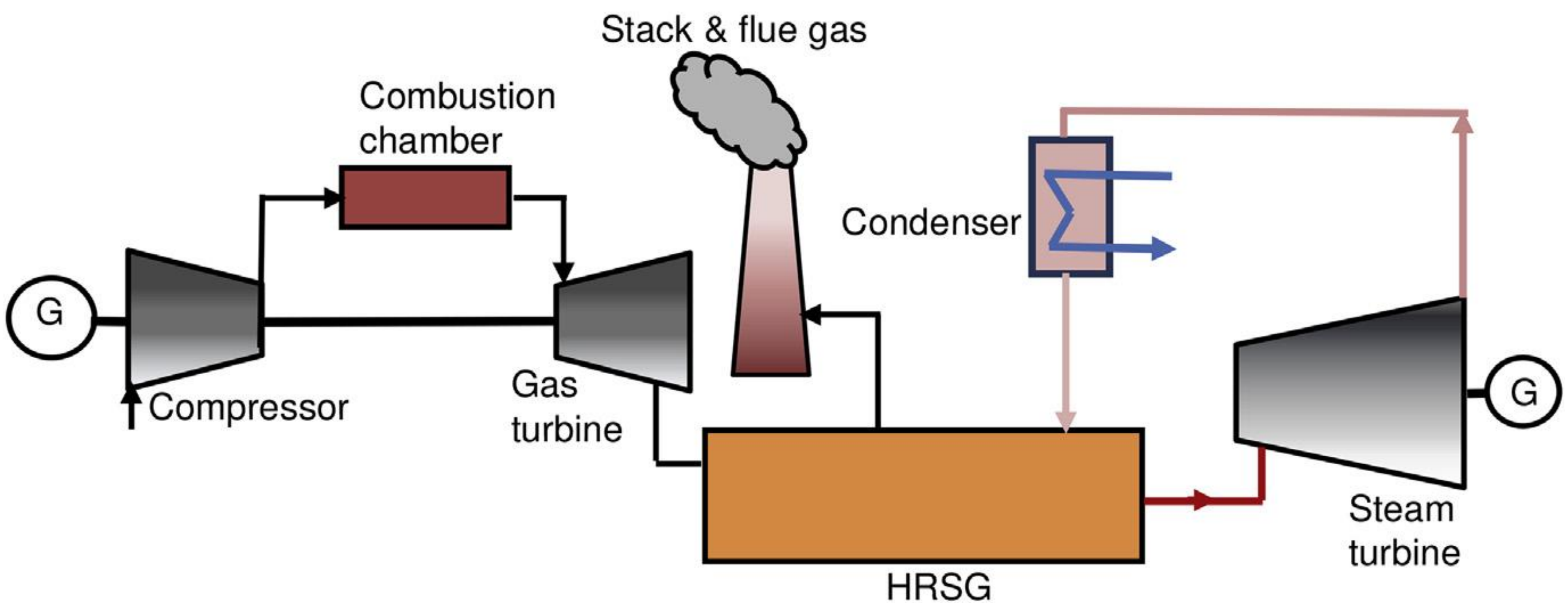


Semiclosed cycle gas turbine: (a) schematic representation of the system and (b) T-S diagram. G =generator, HRSG = Heat recovery steam generator.



Simple closed cycle gas turbine: (A) system and (B) T–S diagram.

One methodology is to introduce a regenerator or a recuperator, i.e. a heat exchanger recovering heat from the hot exhaust gases from the turbine. If this heat is delivered to the compressed air before it enters the combustor, the cycle thermal efficiency will be increased without changing the net cycle work.



Combined cycle gas turbine system with a heat recovery steam generator (HRSG) and generators (G).

Different prospects of VAM utilization

1. **Ancillary use:**
   - (i) as primary air in combustion of middling and rejects of washery in Thermo gravimetric analyzer.
   - (ii) as combustion air in IC engines and its performance evaluation.
   - (iii) as supplementary fuel in rotary kiln system for Syngas production from high ash coal, and for power generation.
2. **Primary use:**
   - as a primary fuel in lean gas turbine by enriching the VAM with CMM drain to produce electricity.
   - as a primary fuel in Thermal Flow Reversal Reactor and its performance evaluation.

- The VAM is used in place of ambient oxygen in the combustion chamber. The calorific value of supplied VAM results in less consumption of primary fuel. **The main draw back of Ancillary use technique is that total VAM is not utilized, only a part of the VAM utilized and remaining portion is vented in the atmosphere.**
- A limited number of technologies that can beneficially use VAM are currently available. One existing approach is quite straightforward and entails using VAM as combustion air, thereby supplying ancillary fuel to internal combustion (IC) engines, turbines, or industrial and utility boilers. Such VAM use in IC engines (running on CMM) has been well-demonstrated in Australia.
- In recent years, technologies have been developed that can destroy very low concentration methane in mine ventilation air by thermal oxidation. The primary purpose of these technologies is the reduction of GHG emissions. Some of these technologies may be combined with a heat recovery system for use at mines or district heating, or to run steam turbines for power generation.

- In case of the Principal use technology, VAM is itself used as a primary fuel in Thermal flow-reversal reactor (TFFR), Catalytic flow-reversal reactor (CFRR), Recuperative gas turbine, Lean burn catalytic turbine and Catalytic monolith reactor (CMR). The minimum methane concentrations required for operation of these technologies are 0.2, 0.1 and 0.4% for the TFRR, CFRR and CMR units, respectively. In these reactors/turbines methane-air-mixture i.e. VAM is fired to generate heat for production energy at small scale.

- Different combustion technologies are summarized in Table 3.

Table 3. Different Combustion Technologies of Ventilation Air Methane [9]

Technology	Oxidation Mechanism	Principle	Application/Status
		Ancillary uses	
Combustion air for conventional Pf power station	Thermal	Combustion in of power station boiler furnace	Mitigation Utilization demonstrated in a pilot scale and being consider for full scale
Combustion air for gas turbine	Thermal	Combustion in conventional gas turbine combustor	Mitigation utilization studied
Combustion air for gas engine	Thermal	Combustion in conventional gas engine combustor	Mitigation utilization studied
Hybrid waste coal/tailing/ methane combustion in a kiln	Thermal	Combustion inside a rotating combustion chamber	Mitigation utilization being preliminary trialed in a pilot scale
Hybrid waste coal/ tailing/ Methane combustion in fluidized bed	Thermal	Combustion inside a fluidized bed and freeboard	Mitigation utilization being proposed as a concept
		Principal Uses	
Thermal flow reverse reactor (TFRR)	Thermal	Flow reverse reactor with regenerative bed	Mitigation demonstrated utilization being planned by BHP Billion
Catalytic flow reverse reactor (CFRR)	Catalytic	Flow reverse reactor with regenerative bed	Mitigation demonstrated, utilization not demonstrated yet
Catalytic monolith reactor (CMR)	Catalytic	Monolith reactor with recuperator	Mitigation demonstrated , utilization not demonstrated
Catalytic lean burn gas turbine	Catalytic	Gas turbine with a catalytic Combustor and recuperator	Mitigation combustion demonstrated utilization being demonstrated at lab scale
Recuperative gas turbine	Thermal	Gas turbine with a catalytic Combustor and recuperator	Mitigation combustion demonstrated utilization demonstrated at pilot scale
Concentrator	Adsorption	Multi stage fluidized/moving bed using a absorbent and desorber	Mitigation utilization under development

- In case of other technologies, Lean burn gas turbine/Micro turbine has been developed to produce power from CMM or enriched VAM.
- Energy development Ltd. (ELD) has developed a recuperative gas turbine that is capable to firing a methane air mixture as low as 1.6%. A Micro-turbine with catalytic combustion power has been developed by Ingersoll-Rand of USA that needed 1% methane in ventilation air.
- Concentrators are also developed to enrich VAM for ready use.

Thermal Oxidation Technologies

- Flow-reversal oxidizers – both thermal and catalytic – are commercially available and are capable of oxidizing VAM.
- VAM entering thermal oxidizers encounters a bed of heat exchange material that has been preheated to the oxidation temperature of methane (1000 °C).
- The VAM oxidizes and releases heat, which in turn maintains the temperature of the heat transfer material at or above 1000 °C, thereby sustaining the auto-oxidation process over time without requiring additional fuel input.
- Valves and dampers repeatedly reverse the flow of incoming VAM to keep the hot zone in the center of the oxidizer.
- Catalytic and thermal systems both operate on this principle, although catalysts allow the reaction to occur at lower temperatures (~800 °C). When VAM concentrations are high enough, these systems can also provide excess heat energy for electricity generation

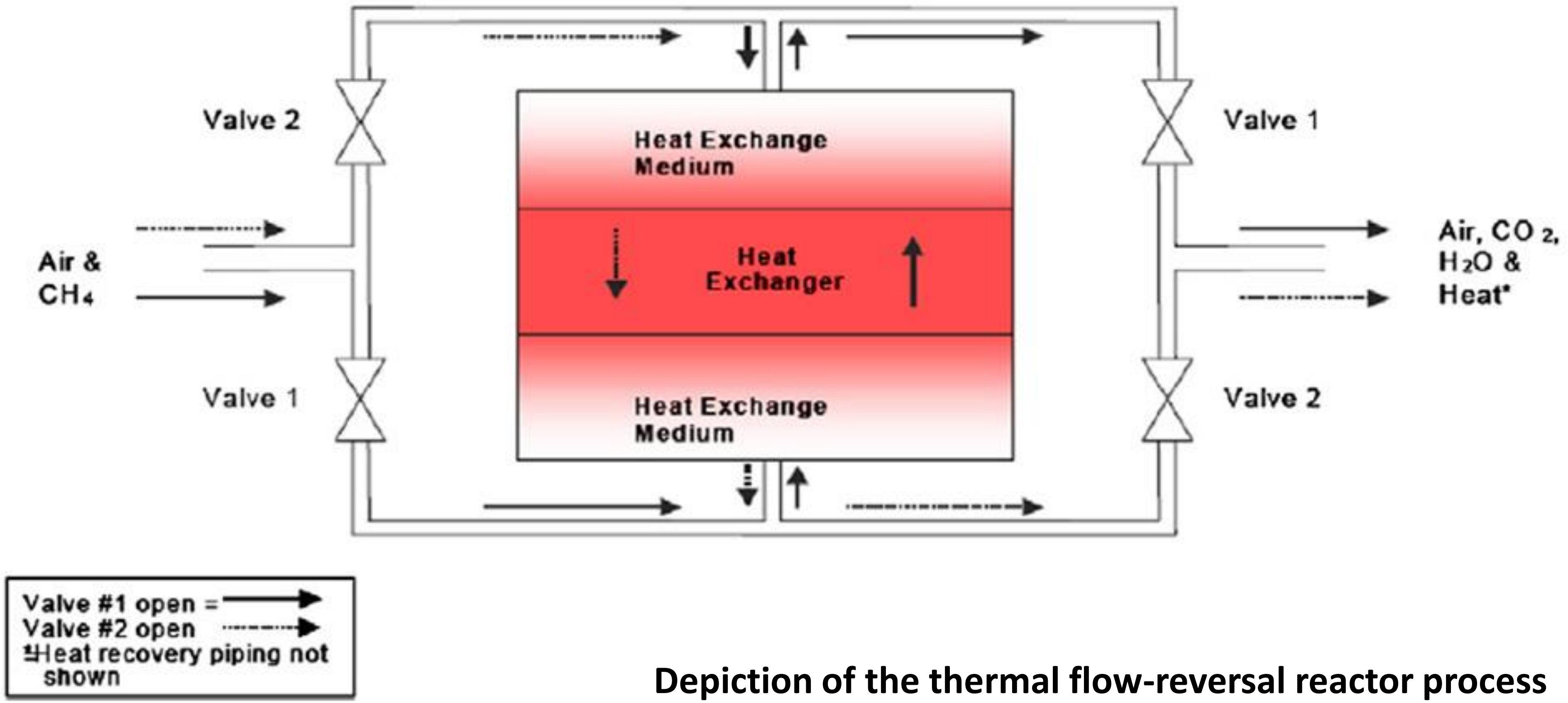
- The U.S. EPA has identified several commercially viable technologies for destroying or beneficially using the methane contained in ventilation air:

1. two technologies based on a thermal oxidation process using thermal flow-reversal reactors (TFRR) also known as regenerative thermal oxidizers (RTO);
2. a catalytic oxidation process called the catalytic flow-reversal reactor (CFRR) also known as regenerative catalytic oxidizers (RCO).

- These technologies employ similar principles to oxidize methane contained in mine ventilation airflows.
- Based on the latest demonstration projects, these units can sustain operation (i.e., maintain oxidation) with ventilation air having uniform methane concentrations down to approximately 0.1% and 0.2% for the CFRR and TFRR processes, respectively.
- For commercial applications where methane concentrations are likely to vary over time, the economic lower concentration limit at which oxidizers will be deployed is 0.5%.
- VAM energy recovery has been successfully demonstrated in Australia, using RTOs to convert VAM to electricity at a mine mouth power plant.
- A VAM RCO has been proven at full-scale demonstration in a test unit.

Thermal Flow-reversal Reactors

- TFRR equipment consists of a bed of silica gravel or ceramic heat-exchange medium with a set of electric heating elements in the center. The TFRR process employs the principle of regenerative heat exchange between a gas and a solid bed of heat-exchange medium. To start the operation, electric heating elements preheat the middle of the bed to the temperature required to initiate methane oxidation (above 1000 °C or 1832 °F, or hotter). Ventilation air at ambient temperature enters and flows through the reactor in one direction, and the air temperature increases until oxidation of the methane takes place near the center of the bed.



Depiction of the thermal flow-reversal reactor process

- The hot products of oxidation continue through the bed, losing heat to the far side of the bed in the process. When the far side of the bed is sufficiently hot, the reactor automatically reverses the direction of ventilation airflow. The ventilation air now enters the far (hot) side of the bed, where it encounters auto-oxidation temperatures near the center of the bed and then oxidizes. The hot gasses again transfer heat to the near (cold) side of the bed and exit the reactor. Finally, the process is reversed again.

Catalytic flow-reversal reactors

- CFRRs adapt the thermal flow reversal technology described above by including a catalyst to reduce the auto-oxidation temperature of methane by several hundred degrees Celsius (to as low as 350 °C or 662 °F).
- CFRR technology was developed exclusively for the treatment of methane in coal mine ventilation air. Injecting a small amount of methane (gob gas or other source) increases the methane concentration in ventilation air and can make the turbine function more efficiently.
- Waste heat from the oxidizer is also used to pre-heat the compressed air before it enters the expansion side of the gas turbine.

- A packed bed, monolith, or other section may be used in the active section of the reactor. Typically, there is also an inert section (either a monolith or packed bed) on either side of the catalyst section that is used to help store thermal energy from the heat of the reaction and transfer that heat to inlet gas as a means of preheating the feed gas. As time progresses, more energy accumulates at the outlet of the reactor.

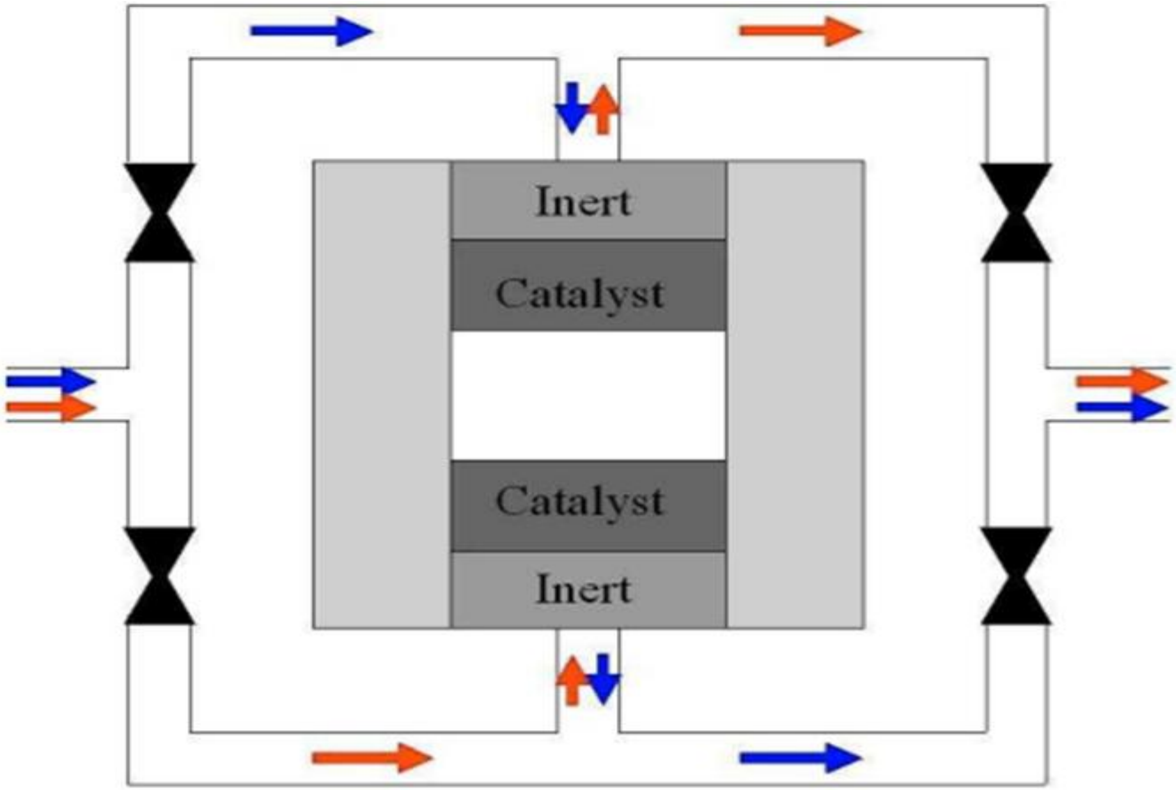


Figure 1-2: The reverse-flow reactor concept. For a determined length of time, the reactor will run in forward flow, indicated by the dark blue arrows. After a determined amount of time, the flow direction will be changed to reverse flow, as indicated by the light red arrows. Surrounding the reactor is a layer of insulation. The open central section may be used for heat or gas extraction. In the experiments presented in this thesis, no heat or gas extraction is used.

- After a determined length of time, the flow direction is reversed, and the thermal energy stored in the inert sections is used to preheat the feed. This time is typically before the reactor begins to lose thermal energy

- Current VAM technologies are generally not able to process methane concentrations below 0.2% without the use of an additional fuel, but research efforts are underway to lower the concentration threshold since VAM concentrations at many mines worldwide fall below 0.2%.
- Operations that use VAM to generate power may need to optimize the inflow concentrations and increase the VAM concentration inlet to the oxidation device.
- One method of fuel enrichment (spiking) involves adding methane from other sources such as gob or pre-mine drainage gas. If enrichment is being considered, low-quality drained gas (less than 30%) should not be used due to the explosion hazard. Use of higher concentration gas (greater than 30%) could divert gas from lower-cost CMM power generation, and this should be evaluated as part of the project feasibility.

EMERGING TECHNOLOGIES

- The U.S. EPA has also identified other technologies that may be able to play a role in and enhance opportunities for VAM oxidation projects. These new technologies include volatile organic compound (VOC) concentrators, lean gas fuel turbines, and using VAM as an ancillary fuel. Each emerging technology is briefly described below:

Concentrators:

- Volatile organic compound (VOC) concentrators offer another possible economical option for application to VAM. Currently, there are three technologies available: the carousel, rotary disk, and fluidized bed, with the fluidized bed considered to be the most applicable technology to concentrating CMM.
- Concentrators operate by passing the methane-laden air up through a bed of adsorbent material (e.g., activated carbon or zeolite beads) on which the methane accumulates, increasing the weight of the adsorbent, which falls downward.
- An inert carrier gas is used to strip the methane in a desorption step; the adsorbent is then returned to the fluidized bed for another concentration cycle.

- The benefits of a concentrator include increasing the concentration of methane in VAM for use in turbines and IC engines, reducing the upgrading requirements for pipeline injection of mid-quality gas, and increasing the commercial use options for low-quality gas streams.

Lean fuel gas turbines:

- Currently efforts are underway to modify selected gas turbine models to operate directly on VAM or on VAM that has been enhanced with more concentrated fuels. These efforts include technologies such as carbureted gas turbines, lean-fueled turbines with catalytic combustors, lean-fueled catalytic microturbines, hybrid coal and VAM-fueled gas turbines, and the use of VAM as an ancillary fuel. These technologies are given below.

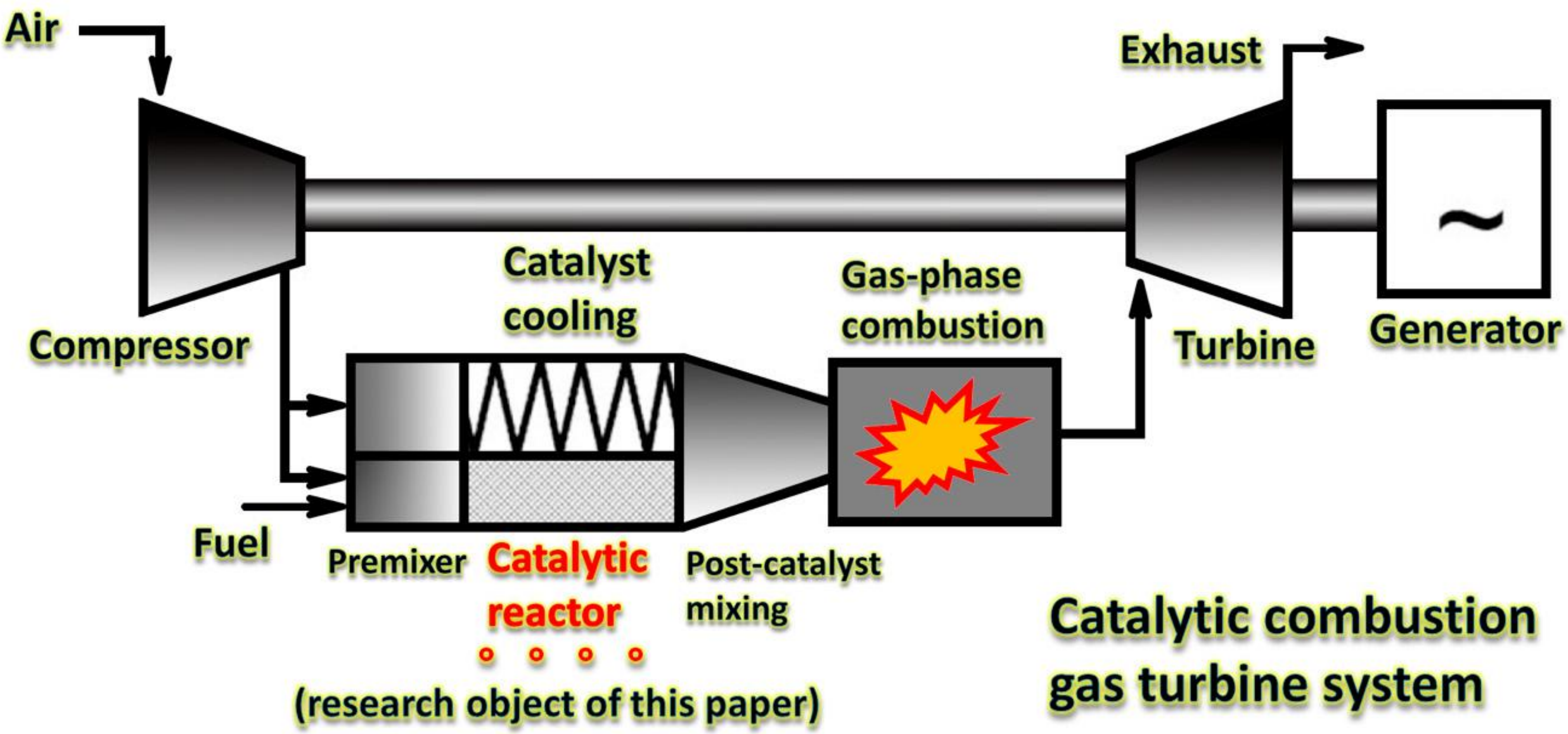
Carbureted gas turbine (CGT)

A carbureted gas turbine is a gas turbine in which the fuel enters as a homogeneous mixture via the air inlet to an aspirated turbine. It requires a fuel/air mixture of 1.6% by volume, so most VAM sources would require enrichment. Combustion takes place in an external combustor where the reaction is at a lower temperature (1200 °C or 2192 °F) than for a normal turbine, thus eliminating any Nox emissions.

Lean-fueled turbine with catalytic combustor (CCGT)

A lean-fueled turbine with catalytic combustor gas turbine is developed by CSIRO (Commonwealth Scientific and Industrial Research Organisation) Exploration & Mining of Australia. This turbine could use methane in coal mine ventilation air and could oxidize the VAM in conjunction with a catalyst. The turbine compresses a very lean fuel/air mixture and combusts it in a catalytic combustor.

A schematic diagram of the catalytic reactor in a catalytic combustion gas turbine system is illustrated in Figure. In this design, fuel and combustion air are premixed in an upstream section: then, only a fraction of the fuel is oxidized in the catalytic section, while the remainder is burned downstream the catalyst in gas-phase combustion mode. The present work focuses on the low-temperature oxidation reaction taking place in the catalytic reactor.



Lean-fueled catalytic microturbine

A lean-fueled catalytic microturbine is being jointly developed by two U.S. companies, FlexEnergy and Capstone Turbine Corporation. The application will start at 30 kW and will operate on a methane-in air mixture of 1.3%. Capstone microturbines have been successfully demonstrated utilizing CMM at an abandoned mine in Japan in 2004.

Hybrid coal and VAM-fueled gas turbine

CSIRO (Commonwealth Scientific and Industrial Research Organisation) is developing a system to oxidize and generate electricity with VAM in combination with waste coal. CSIRO is constructing a 1.2-MW pilot plant that co-fires waste coal and VAM in a rotary kiln, captures the heat in a high-temperature air-to-air heat exchanger, and uses clean, hot air to power a gas turbine.

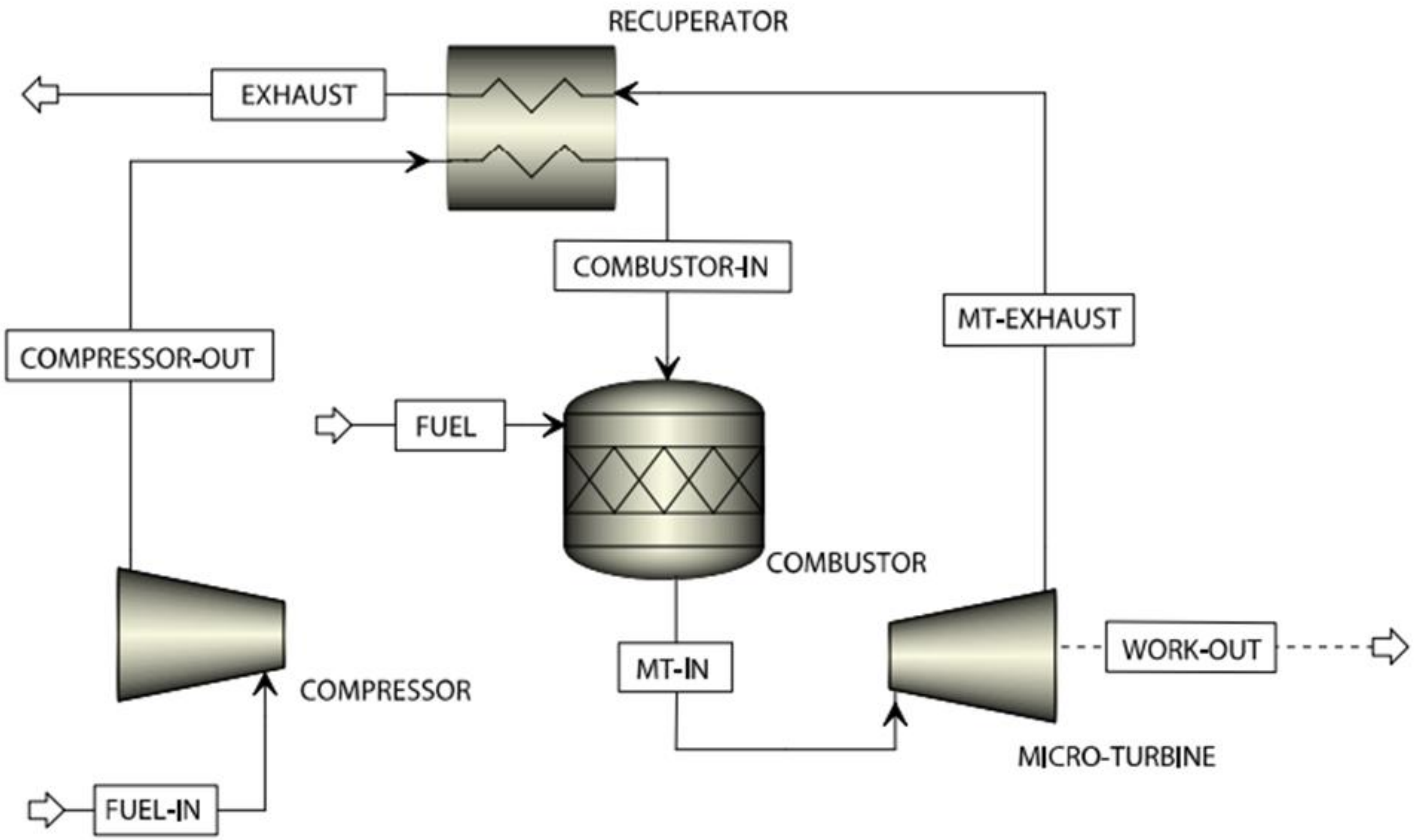


Fig 15. Schematic of Micro-gas turbine cycle.

- The Hybrid Coal Gasification Technology (HCGT) developed by CSIRO (Commonwealth Scientific and Industrial Research Organisation), Australia wherein washery middling along with low concentration of methane is combusted in a Rotating Kiln to produce hot gas to generate electric power.
- The HCGT plant requires air with minimum 0.3% methane at the rate of 4000m3/min. and washery middling whose Calorific value ranges from 3000 to 3500kgcal at rate of 11.75t/hr in two Rotating Kilns. The plant generates steam at the rate of 60t/hr which is used in steam turbine to produce 12MW electric power. The diagram of HCGT plant is shown in Figure 2.

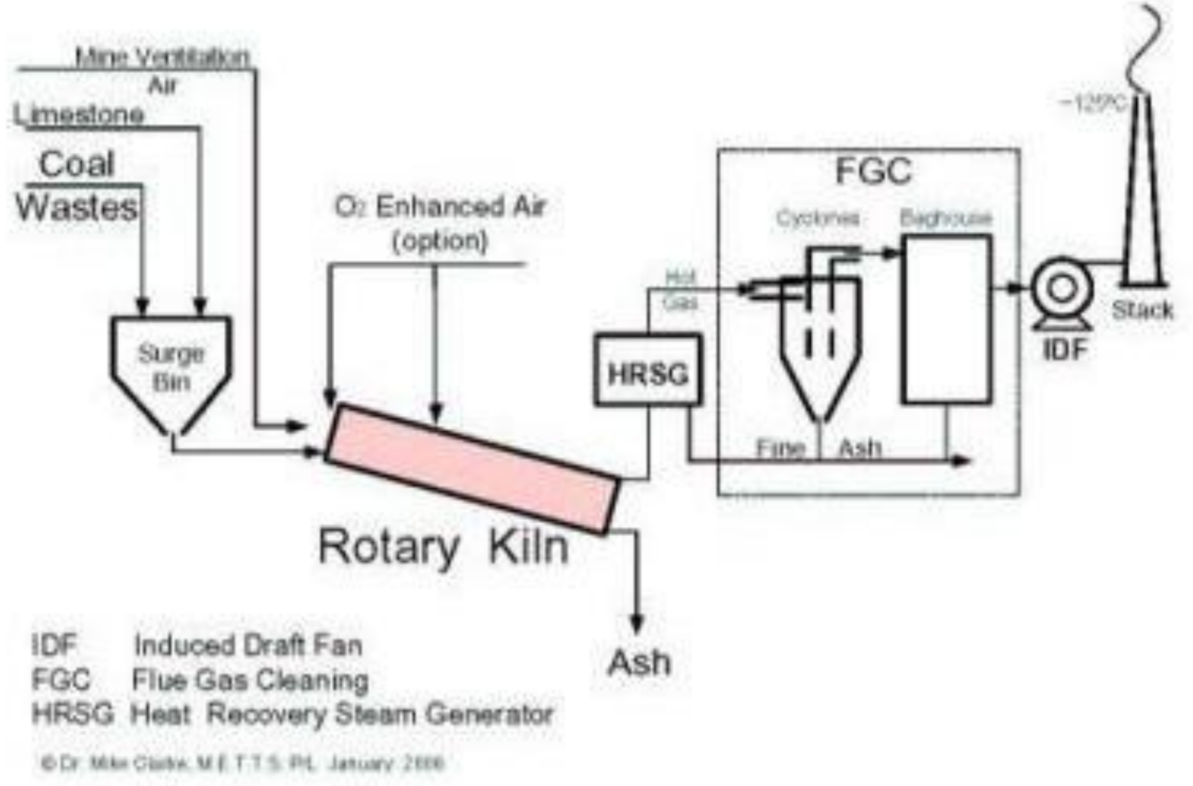


Fig. 2. Schematic diagram of HCGT plant

Summary of advantages and disadvantages of end-use technologies.

Use	Applications	Advantages	Disadvantages
High-quality pipeline gas	Purified high-quality CMM.	• Natural gas equivalent.	• Pipeline purity standards are high and purification is costly.
		• Profitable where gas prices strong.	• Only feasible for high-quality, pre-drained CMM or treated CMM.
		• Good option where strong pipeline infrastructure exists.	• Requires reasonable access to pipeline.
Power generation	Gas-engine generators producing power for mine use or export to the grid.	• Proven technology.	• Interruptible and variable output; therefore, may not be conductive for the electric grid.
		• Waste heat recovery for heating mine buildings, miner baths, and shaft heating and cooling.	• Regular maintenance requires commitment of mine operator.
			• High capital costs at initial stage of project.
VAM flow reversal oxidizers	Destruction of dilute concentrations of methane often less than 1% in VAM. Potential for waste heat recovery for energy generation.	• Destruction of large source of CMM emissions.	• High capital costs at initial stage of project.
		• Can capture waste heat for water or space heating.	• Regular maintenance requires commitment of mine operator.
VAM as combustion air	Using VAM as combustion air to supply ancillary fuel to combustion devices.	• Destruction of large source of CMM emissions.	• High capital costs at initial stage of project.
		• Can be used to generate electricity for onsite or offsite use.	• Regular maintenance requires commitment of mine operator.
Medium-quality "town" or industrial gas	>30% methane for local residential, district hearing and industrial use such as firing kilns.	• Low-cost fuel source.	• Cost of distribution system and maintenance.
		• Localized benefits.	• Variable quality and supply.
		• May require minimal or no gas cleanup.	• Costly gas holders needed to manage peak demands.

Summary of advantages and disadvantages of end-use technologies.

Use	Applications	Advantages	Disadvantages
Chemical feedstock	High-quality gas for the manufacture of carbon black, formaldehyde, synthetic fuels, and di-methyl ether (DME).	• A use for stranded high-quality CMM supplies.	• High processing cost. • No CDM potential when carbon can be liberated.
Mine Site	Heating, cooking, boilers, coal fines drying, miner's residences.	• Displaces coal use. • Clean, low-cost energy source.	• May be less economically beneficial to use onsite than off-site.
Vehicles	Purified high-quality, pre-drained gas and CBM for CNG and LNG.	• Market access for stranded gas supplies. • Vehicle fuel prices are very high.	• Processing, storage, handling, and transport costs. • Purification standards are very high.
Flaring	Destruction of drained CMM or excess CMM from other utilization technologies.	• Generally low-cost destruction option. • Destruction efficiencies between 98% and 99%.	• Generally requires a methane concentration of 30%. • Concerns over safety of flares at mining locations.

CASE STUDY

Options For Methane Recovery and Energy Generation

Coal mine project opportunities in some of the selected collieries in India

- In a recent feasibility study funded by the US Environmental Protection Agency (US EPA), Kalidaspur and Ghusick collieries in the Raniganj Coalfield, Murulidih, Amlabad, Sudamdih and Parbatpur mines in the Jharia Coalfield and Jarangdih and Sawang collieries in the East Bokaro Coalfield appear to be promising sites for CMM recovery at first glance. CMM resources in the above collieries in the Damodar River Basin in India have been estimated and are presented in Table 6.

Table 6. Important collieries for coal mine methane extraction.

Name of the colliery	Name of Coal field	Degree of Mine	CMM resource (Billion cubic meter)
Kalidaspur	Raniganj	III	3.783
Ghusick	Raniganj	III	2.58
Murulidih	Jharia	III	4.98
Amlabad	Jharia	III	0.76
Sudamdih	Jharia	III	0.80
Central parbatpur	Jharia	III	5.31
Jarangdih	East Bokaro	III	4.87
Sawang	East Bokaro	III	6.31

- Gas resources in Ichhapur, Kulti and Sitarampur blocks in the Raniganj Coalfield and Asnapani and Kathara blocks in the East Bokaro Coalfield have been estimated and are presented in Table 7.

Table 7. Important blocks for coal mine methane extraction.

Name of the block	Name of Coal field	Area (Sq km)	Status of the block	CMM resource (Billion cubic meter)
Ichhapur	Raniganj	12	Virgin	3.83
Kulti	Raniganj	7.8	Virgin	1.77
Sitarampur	Raniganj	9	Virgin	1.63
Kapuria	Jharia	6.4	Virgin	1.51
Asnapani	East Bokaro	4	Virgin	6.64
Kathara	East Bokaro	6	Virgin	8.62

- Kalidaspur colliery is a degree III mine in the Raniganj coalfield with an average production of 350 tonnes per day. The rate of methane emission was found to be more than 10 cubic meters per tonnes of coal mined during the days of investigation. The minimum and maximum values of rate of methane emission per tonnes of coal production were 8.78 and 19.27 cubic meter per tonnes respectively. The CMM resource estimated for Kalidaspur Colliery including the adjoining virgin Bakulia Block was 3.783 billion cubic meters (BCM). Thus, it is qualified to be a potential site for a small scale CMM project.

- Ghusick colliery is also a degree III underground coal mine in the Raniganj coalfield. This colliery was found with very high level of gas at shallow depth. During the investigation period it was found that make of methane varied between 11.02-14.2 m3/minute even when the production was only 70 tonnes of coal per day. Also, the gases obtained from the sealed-off areas, when analyzed, contained 50-65% of methane. An estimated CMM resource of 2.58 billion cubic meters (BCM) was found at the Ghusick colliery. Thus , the venture of CMM degasification and Gob degasification can be accomplished at the Ghusick Colliery.

- Ichhapur, Kulti and Sitarampur are the virgin coal blocks of Raniganj coalfield having a maximum value of in-situ gas content of 7.06 m3/t, 9.16 m3/t and 7.21 m3/t respectively. The CMM resource of Ichhapur Block was found to be 3.83 BCM and it is suitable for small scale CMM project. The total gas resource of 3.40 BCM is present in the Kulti and Sitarampur Blocks, therefore these blocks can be developed as a site for medium scale CMM project.

- In the Jharia coalfield, Murulidih, Amlabad, Sudamdih and Parbatpur are important collieries for CMM extraction.
- Murulidih mine lies in the Mahuda sub-basin area and is designated as degree III mine. With a CMM resource of 4.98 BCM in the Raniganj and deep Barakar formations, Murulidih colliery can be considered for medium scale CMM project.
- Amlabad and Sudamdih Collieries also have high levels of gas, and at relatively shallow depths. Both the mines are Degree III gassy mines. The rate of methane emission is 25 m3/t of coal production at the Amlabad Colliery making it very difficult for coal mining. It has an estimated gas resource of 0.76 BCM. The nearby Sudamdih mine is having a gas resource of 0.80 BCM. Therefore these two collieries can be modeled as small scale CMM ventures.
- Central Parbatpur is located to the South of Damodar River in the South Eastern part of Jharia coalfield, covering an area of about 8.8 sq km. This area is characterized by significant tectonic disturbance and is cris-crossed by 11 major faults. Central Parbatpur is having a CMM resource of 5.312 BCM, representing a rich site for CMM extraction and recovery.

- East Bokaro Coalfield is a huge storehouse of high rank medium coking metallurgical coals. Jarangdih and Sawang are two underground Degree III collieries with a known history of gassiness. The rate of methane emission per tonne of coal produced at the Jarangdih 6 ft seam at the Jarangdih colliery mine was insignificant but a value of 17.12 m3/t methane emission was observed in the Jarangdih 6 ft seam at the Sawang colliery.
- Two important virgin blocks namely Asnapani and Kathara located in the south central part of East Bokaro Coalfield, having a surface area of 4 sq km and 6 sq km respectively provide an option for CMM extraction and recovery. The Asnapani block is containing a CMM resource of 6.64 BCM and Kathara Block with a CMM resource of 8.62 BCM can be easily chosen for CMM projects location.

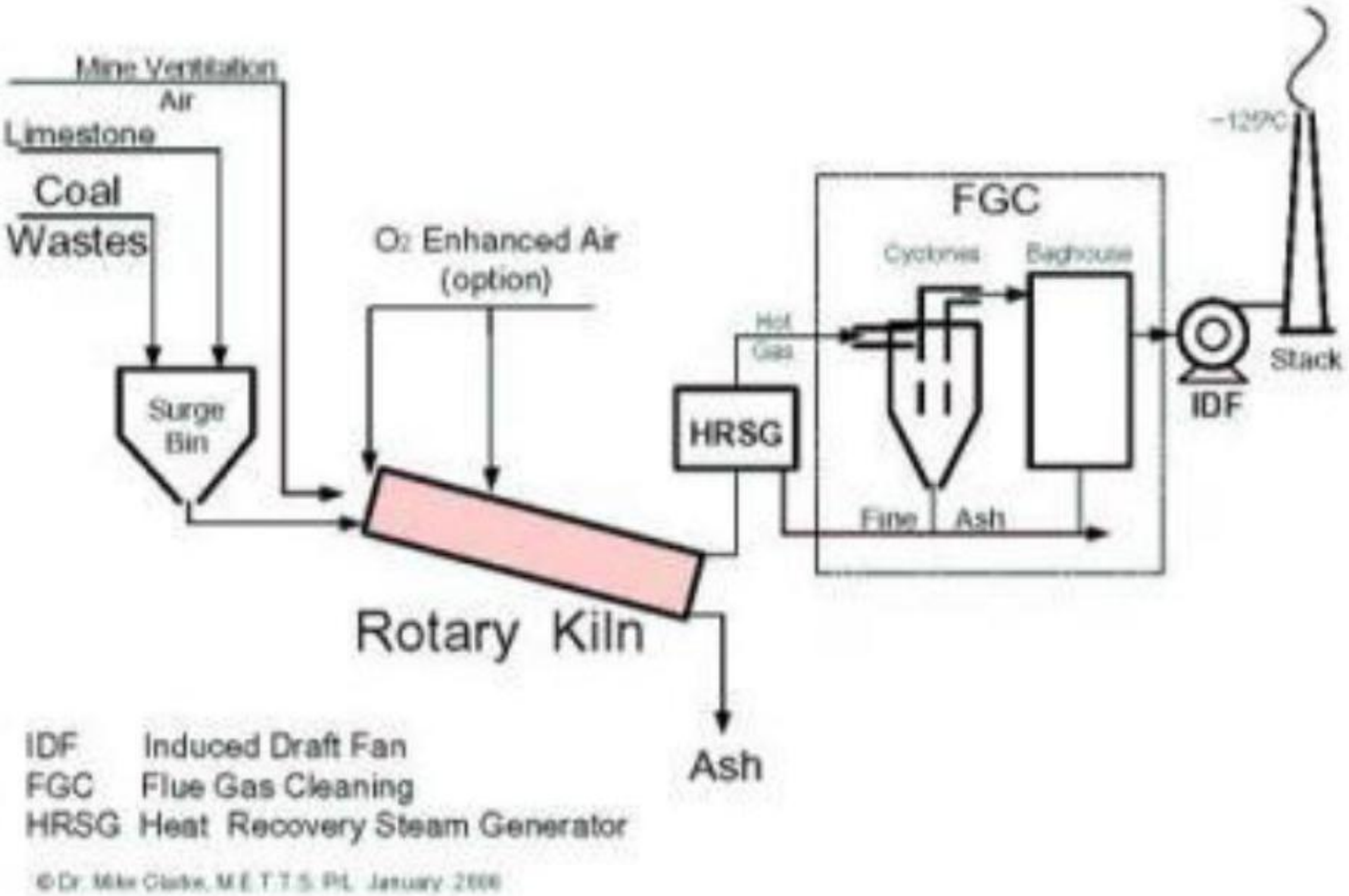
VAM Project Opportunities in India

- There are 13 degree III mines in India (Table 1) and wherein VAM utilization is feasible. CSIR-CIMFR along with Southern Illinois University Carbondale (SIUC), USA completed a study to evaluate the resource potential of VAM utilization at Moonidih and Sudamdih mines in the Jharia Coalfield.

Table 1.Underground working mines having different degree of gassy seam – 2012. [18]

State	Degree I	Degree II	Degree III	Total
Andhra Pradesh	41	...	...	41
Assam	...	....	02	02
Chhatisgarh	42	...	01	43
Jharkhand	61	26	07	94
Jammu and Kashmir	01	02	...	03
Madhya Pradesh	39	16	...	55
Maharashtra	22	...	...	22
Orissa	07	03	...	10
West Bengal	24	56	03	83
All India	237	103	13	353

- Further studies were conducted by CSIR-CIMFR for assessment of quantity and quality of the mine air and characteristics of washery middlings at Moonidih mine of Coal India Limited which is a Degree III gassy mine and concentration of methane in the return air varies from 0.3 to 0.6%.
- Further, Moonidih Mine has its own washery and has surplus middlings too. Hence, Moonidih was chosen for feasibility study for implementation of Hybrid Coal Gas Technology (HCGT) developed by CSIRO, Australia wherein washery middling is combusted along with ventilation air methane in a rotary kiln to produce hot gas for production of electric power.
- The process includes the collection of air with a minimum 0.3% methane concentration at the rate of 12000 m3/min from the mine exhaust and feeding it to the rotary kiln where it may be combusted with washery middling at the rate of 11.75 tonne/hour. The hot gas coming out of the rotary kiln will be supplied to a waste heat recovery boiler (WHRB). The steam produced by the boiler at the rate of 60 tonnes per hour will be used in a steam turbine generator which will produce nearly 12 MW power.


Mine Ventilation Air
Limestone
Coal Wastes
Surge Bin
O2 Enhanced Air (option)
Rotary Kiln
Ash
HRSG
Hot Gas
FGC
Cyclones
Baghouse
Fine Ash
IDF
Stack
IDF Induced Draft Fan
FGC Flue Gas Cleaning
HRSG Heat Recovery Steam Generator

Calculation of Net Emission Reduction for VAM Project at Moonidih Mine

- For calculation of net emission reduction, the input parameters are assumed as air flow rate from the return of coal mine is 12,000 m3/min and the concentration of methane in the return air as 0.5%. A significant reduction of 0.62 million tonnes of CO2 per year is possible with the use of VAM. The important parameters are reflected in the Table 8.

Table 8.Analysis of net emission reduction by using VAM for Moonidih coal mine.

Sl.no	Description	Quantity	Unit
1.	VAM fed to Rotary kiln	12,000	m^3/min
2.	Average concentration of methane in VAM	0.5	%
3.	Volume of methane consumption in rotary kiln	3.154×10^7	m^3/year
4.	Consumption of methane in rotary kiln	2.253×10^4	tonnes/year
5.	Net GCV with available methane quantity (Considering GCV of CH_4=33402 kJ/m^3)	1.0535×10^{12}	kJ/year
6.	Heat available for power generation (considering 26% efficiency)	2.739×10^{11}	kJ/year
7.	Electricity generation with available heat (Considering 1kJ=2.7×10^{-4}kWh)	7.395×10^7	kWh/year
8.	CO_2emission from grid for available electricity (Considering CO_2intensity of grid as 0.82 kgCO_2/kWh)[2]	6.063×10^4	tonnes of CO_2/year
9.	CO_2avoided by consuming methane (considering GWP of CH_4= 28)[3]	63.084×10^4	tonnes of CO_2/year
10.	CO_2 generated due to combustion of CH_4 in Kiln	6.195×10^4	tonnes of CO_2/year
11.	Net CO_2 reduction by utilizing VAM	62.952×10^4	tonnes of CO_2/year

A.1. Calculation of net emission reduction for VAM project at Moonidih Mine

Air flow rate from the evasee is 12000 m^3/min that may be fed to the rotary kiln.
Then the Air flow rate per annum
$= 12000 \times 60 \times 24 \times 365$
$= 6307200000\ m^3$/year

Considering the average concentration of 0.5% methane in VAM, methane consumption per annum will be
$(0.5 \times 6307200000)/100$
$= 31536000\ m^3\ CH_4$/year
$=3.154 \times 10^7\ m^3 CH_4$/year

This will be fed to one rotary kiln. Therefore, methane consumption per annum for one rotary kiln can be calculated as below:
CH_4 consumption per annum per rotary kiln
$= 3.154 \times 10^7\ m^3 CH_4$/year
$= 3.154 \times 10^{10}$Liters/year
$= (3.154 \times 10^{10}/22.4)$ g-moles per year
$= (3.154 \times 10^{10}/22.4) \times 16$ gram/year
$= 2.2528 \times 10^{10}$ gram/year
$= 2.253 \times 10^4$ tonnes/year

The complete oxidation of methane takes place, according to the following chemical reaction.
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
It means 16g of CH_4 produces 44g of CO_2.
Therefore, 2.253×10^4 tonnes/year of methane will generate (2.253×10^4 tonnes/year) $\times 44/16$ tCO_2eq/ year
$= 61957.5\ tCO_2eq$/ year
$=6.195 \times 10^4\ tCO_2eq$/ year
Thus a quantity of **$6.195 \times 10^4\ tCO_2eq$/ year** will be generated by rotary kiln due to combustion of methane.

Now, GCV of methane
= 33402 kJ/SCM
Net GCV available
$=33402 \times 3.154 \mathrm{x} 10^7$ kJ/year
$=1.0535 \times 10^{12}$ kJ/year

Assuming an efficiency of 26%, the heat that is available for power generation
$= 0.26 \times 1.0535 \times 10^{12}$ kJ/year kJ/year
= 2.739×10^{11} kJ/year
We know that
1 kJ = 2.7×10^{-4} kWh
Therefore, electricity generation possible with the available heat per kiln
$= 2.739 \text{x} 10^{11} \times 2.7 \times 10^{-4}$ kWh/year
= 73955635.42 kWh/year
=7.395×10^{7} kWh/year

If $7.395 \text{x} 10^{7}$ kWh/year of electricity were purchased from the Eastern Region Grid of India, the amount of CO_2 generated, considering the carbon intensity of grid as 0.82 kg CO_2/kWh will be equal to
$0.82 \times 7.395 \text{x} 10^{7}$ kg CO_2 eq/year
= 60639000 kg CO_2 eq/year
= **6.0639×10^{4} tCO2 eq/year**

Since the available 2.253×10^{4} tonnes/year of methane will be consumed by the VAM based HCGT power plant
Therefore, an equivalent amount of $2.253 \times 10^{4} \times 28 = 630840$ tCO_2eq/ year
= **63.084×10^{4} tCO_2eq/ year**
will be prevented from escaping to the atmosphere.

Net emission reduction will be:
(**$63.084 \times 10^{4} + 6.063 \times 10^{4} - 6.195 \times 10^{4}$**) tCO_2eq/ year.
= **62.952×10^{4} tCO_2eq/ year**

ECONOMICAL ANALYSIS

- To assess the technical and economic feasibility of a mine-site implementation of any potential mine methane technology, it is necessary to first understand the methane emission characteristics from that mine. In order to determine the potential to continuously operate methane mitigation and utilization plants at a mine site, the following mine-site data are required:

1. Percentage of methane emitted from ventilation air stream,
2. Variations in methane concentration and flow rate for ventilation air, and
3. Methane concentration variation rate.

- In order to discuss economical benefits, the quantification process of VAM from a particular mine is required to be studied. It is estimated on the basis of rate of methane emission per tonne of coal produced.

- Economical analysis has been studied on the basis of utilization of ventilation air methane.
- Moonidih mine in Jharia Coalfields is a mechanized mine and is of degree III gassy mine. Investigation on the quantification of VAM has been conducted under a UNDP (United Nations Development Programme) project. The concentration of methane in VAM ranges between 0.11 to 0.22% at 510 TPD during coal mining from XV and XVI seams and it is 0.11% during idle period i.e. when no coal production. The total quantity of VAM at the current rate of production was calculated for 2007-08 and is presented in the Table 4.

Table 4. VAM estimation for Moonidih mine in Jharia Coalfields

Parameters	Rate/Production
Ventilation air quantity	$12000m^3$/minute
Ventilation Air discharge in one day	$17.28Mm^3$
Ventilation Air discharge in one year	$6.3Tm^3$
VAM emitted @ 0.1%CH4 (v/v)	$6.3Mm^3$
VAM emitted @ 0.2%CH4 (v/v)	$12.6Mm^3$
Average VAM estimate per year	$9.5Mm^3$
Quantity of VAM emission per year	6342T

- With increasing production of coal in future and availability of low rank coal (washery middling) from Moondih coal washery situated nearby mine site, the HCGT plant may be installed under a clean development mechanism project for the utilization of VAM.

- An economical analysis based on VAM utilization of Moonidih mine of Bharat Coking Coal Limited in Jharia Coalfields is discussed and results are shown in the Table 5. Generation of CO2 by VAM utilization has been balanced during assessment of economical benefit. Other investments such as capital cost to establish HCGT plant, purchase of low rank coal and selling of generated electric power are not considered due to lack of component costs. In one Rotary kiln, 4505 Tonne per year methane may be combusted and generated revenue by selling CERs may be 0.64 million dollar (Rs. 383 Lakh) per year.

Table 5. Economical analysis by using VAM with Low rank coal

Parameters	Rate/Production
Ventilation air consumption by the Rotatory Kiln	$4000m^3$/min.
Methane concentration in ventilation air	0.3% CH_4
Use of VAM per minute	$12m^3$ CH_4
VAM used by one rotating Kiln per annum	$6307200m^3$ CH_4
VAM used by one rotating Kiln per annum	4505Tonne CH_4
Used VAM by Rotating Kiln	12389t eq. CO_2
Global warming effect of CH_4 compare to CO_2	21times
Net CO_2 reduction by Rotating Kiln	91226t Eq. CO2
Rate of certified emission reduction (CER)	$7.00
Revenue generated by one Rotating Kiln per annum	$638582
Revenue generated in Rupees (1$=Rs.60) per annum	Rs.38314920.00