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CoMeth

Coal Mine methane – New Solutions for Use of CMM – reduction of GHG emissions

Collaborative Project

Thematic priority: EN

Basics on technologies for utilisation of CMM

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Preamble

Methane is the main greenhouse gas that is related to coal production. It is produced from underground and surface mines, and results from post-mining activities including coal processing, storage, and transportation. The energetic utilisation of CMM e.g. by electric power generation in CHP, co-firing in boilers, contributes to the conservation of fossil fuels, to the diversification of energy resources, and to the reduction of climate-relevant emissions.

Depending on the composition and the quality of coal mine methane (CMM) different technologies for its utilisation are available. This report does not focus on the detailed technologic description of each technology. In fact first an overview about different forms of coal mine methane is outlined and finally a brief overview about the relevant technologies is given. Main characteristics in respect to their applicability for CMM utilization as well as the resulting requirements regarding CMM quality and amount are highlighted. In order to describe some solutions also manufacturer instructions are included, especially for technologies for which no or only few application experiences exist.

This report can be used as a first assistance to judge the suitability of the available technologies for energetic utilisation of CMM, but do not release the user from detailed investigation. Thence a couple of references are included delivering more and detailed information about the potential CMM utilization technologies.

1 Coal mine methane

The major part of methane in coal mines is gas deliberating from the broken coal in the surroundings of the longwall and from dug part of the mine. Depending on the location and period of its disposal to the atmosphere, CMM can be divided into 3 classes, as shown in the figure below.

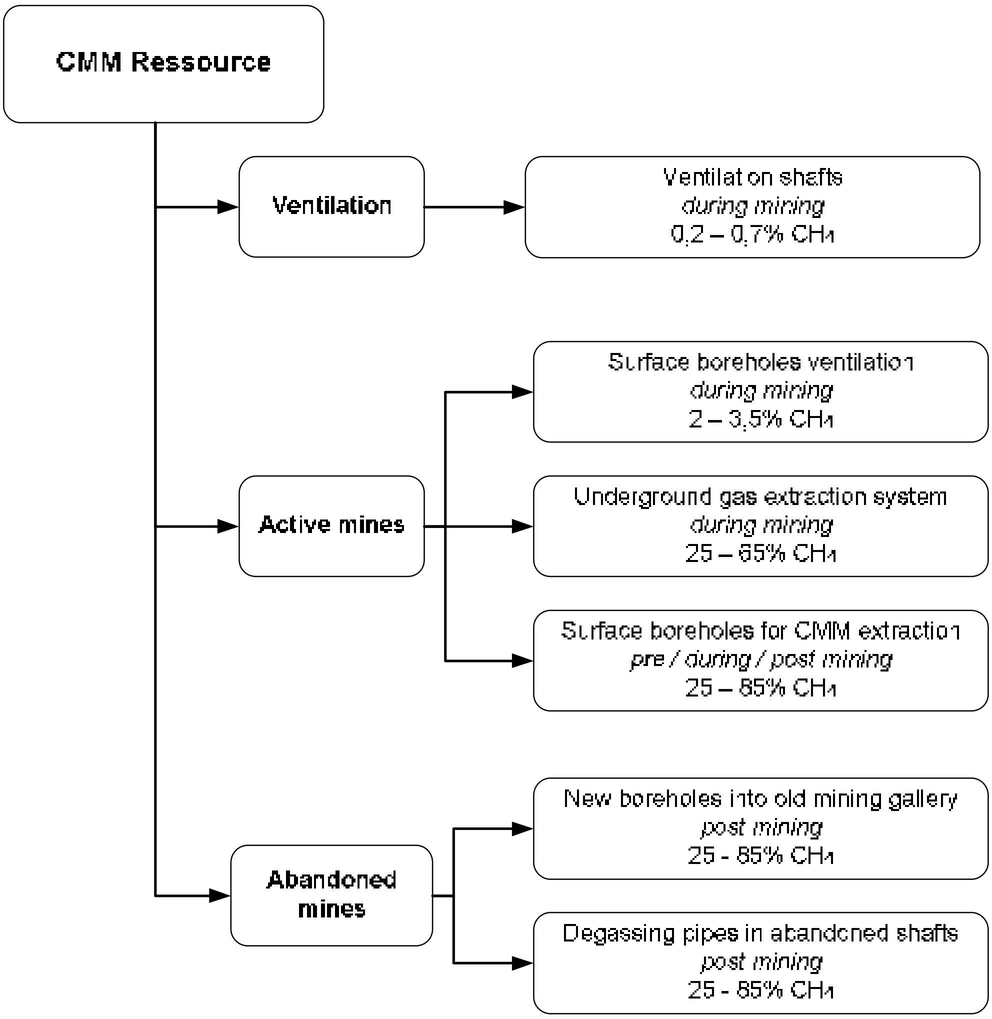


Fig. 1-1: Classes of CMM

1.1 VAM (ventilation air methane)

According to figure 1-1 ventilation air methane (VAM) is a gas mixture with a very low content of methane. At the same time it is the major source of methane emitted in the atmosphere. Each mine operates ventilation systems which deliver big amounts of air into the underground infrastructure. With the ventilation air flow methane, desorbed from the broken coal during the mine operation, can leave the mine through the shafts. According to authority requirements, made to ensure the mine safety, the maximum concentration of methane is limited to 1 % CH_4 in every part of the ventilation system of a coal mine. Typical methane concentrations in the ventilation air are in the range between 0,2 % and 0,7 % CH_4. The exhausted air from a mine is a mixture of different ventilation ways and the concentration of methane in VAM is nearly everywhere less than 1 %.

As long as the released methane can be totally transported out of the coal mine by the ventilation system (< 1% CH_4) no separate degassing system is needed. It is simpler and cheaper for the mine operation. Therefore more than 50 % of the total methane of coal mines is released to atmosphere through the ventilation system.

However, in deep mines with high methane content in the coal and high coal production, the biggest part of the released methane has to be captured by a degassing system (refer to chapter 1.2). Only the remaining part of the methane is disposed by the ventilation air system.

1.2 CMM (Coal Mine Methane)

In many coal mines the ventilation system is not able to ensure the safe underground atmosphere and methane has to be captured by a special degassing system. This air - methane mixture which is collected by the degassing system is called CMM.

1.2.1 Central degassing system and the underground gas extraction grid

The most installed systems in active mines in Western Europe are central gas compressor stations connected to the degassing grid which interlinks each degassing point in the underground. The depression needed for the operation of the grid is about 100 mbar. Through a smart adjustment of the degassing points up to 80% of the released gas can be captured by the degassing system and be extracted.

1.2.2 Local degassing boreholes - surface borehole CMM extraction

Another solution applied in other regions of the world is methane extraction from the (future) operational mine area through special degassing boreholes drilled from the ground level down to the coal layer. The boreholes are in some mines drilled direct into the coal layer. It is also possible to stop the drilling some meters above the coal seam. In case of CMM capture prior of coal mining, dewatering of the boreholes is usually not necessary.

Methane can be vented to the atmosphere through the degassing boreholes before start of coal extraction in the related part of the mine. The volume of exhausted methane is strong variable and depends on the local geological conditions. A condition for a succesfull extraction by means of that system is high porosity of the coal seam and the surrounding rocks.

Whereas at some locations big volumes of methane deliberates by itself with methane pressure values up to 80 bar, in most places only a small volume of methane releases from the virgin coal seam. The degassing can in such cases be extended through depression from a compressor station.

Typically the methane concentration of CMM captured in this way is very high, often more than 90% CH_4 at the beginning of CMM extraction. Until the underground works has not reached the borehole the methane concentration stays at a high level. When the cracks caused by the mining activities reach the borehole, the underground ventilation air get through into the boreholes. The effect is increased gas mixture´s volume with lower methane contents Fig. 1-2 shows the characteristic development of gas flow and methane concentration when the long wall face passes the borehole.

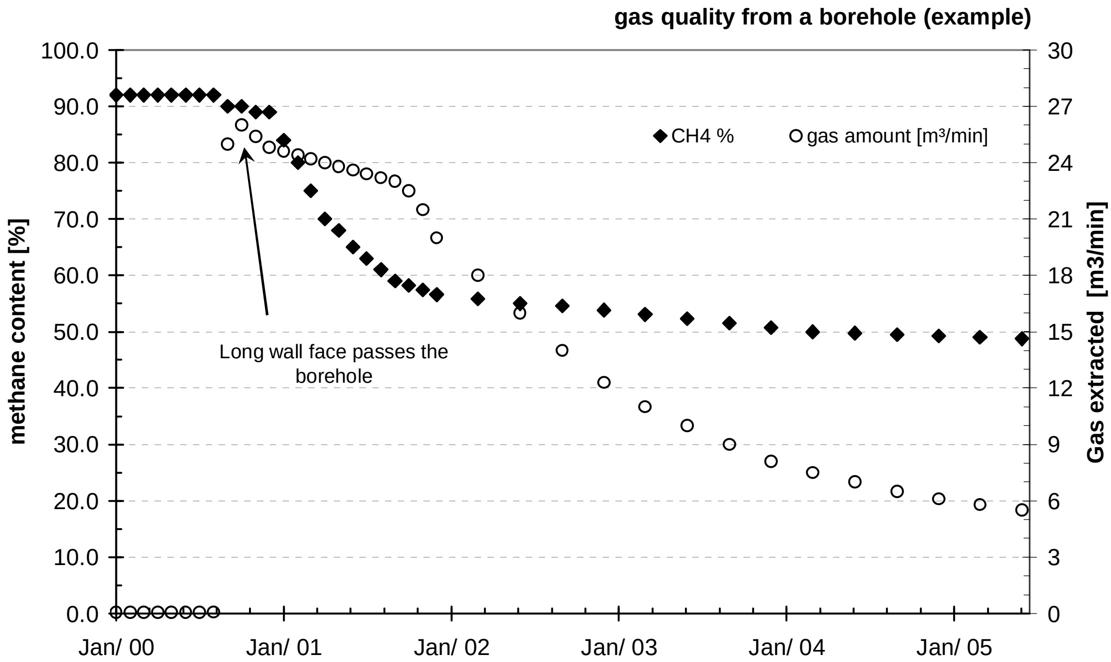


Fig. 1-2: Characteristic development of gas flow and CH_4-content of CMM sucked at a borehole (source: Fraunhofer UMSICHT)

The released gas volume from the coal increases rapidly from a rate of 0,05m³/min up to more than 20 m³/min.

A long gas production period can be ensured by a proper borehole casing due to avoid a collapse of the borehole in the future.

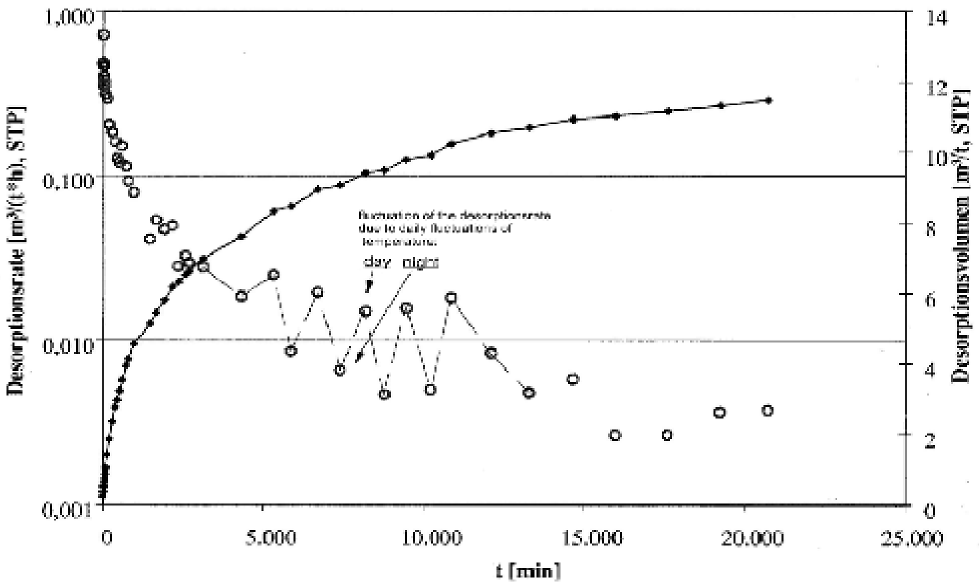


Fig. 1-3 Desorption of methane from a coal sample. [1]

Different boreholes along one longwall may cause different CH_4-concentrations by various gas flows, similar as shown with a coal sample in Fig. 1-3. In case of low methane concentrations the volume flow has to be reduced. Therefore a separate volume flow regulation of each borehole is recommendable to reach an effective degassing by boreholes. For this reason each one needs a valve in the connection between the borehole and the collecting pipe.

1.2.3 Local ventilation boreholes - surface borehole ventilation air

In some countries, especially in Russia, degassing of the gob area is done by a ventilation borehole. Even big boreholes with a diameter up to 2 are restricted to ventilation; no persons or material are allow to be transported through it. The ventilation shaft connects an old gallery behind the longwall with the ground level. The volume of air and gas extracted can reach values up to 2,000 m^3/min with methane concentrations lower than 4 % , which is too low for use in engines or burners. Depending on the methane concentration the gas air mixture can be explosive and an utilisation is up to day not implemented.

Boreholes may have lifetimes of some years as production of methane in the mined area continues for a longer time and active parts of the mine have to be still kept safe.

An example for a degassing system by means of boreholes is shown in the Fig. 1-4

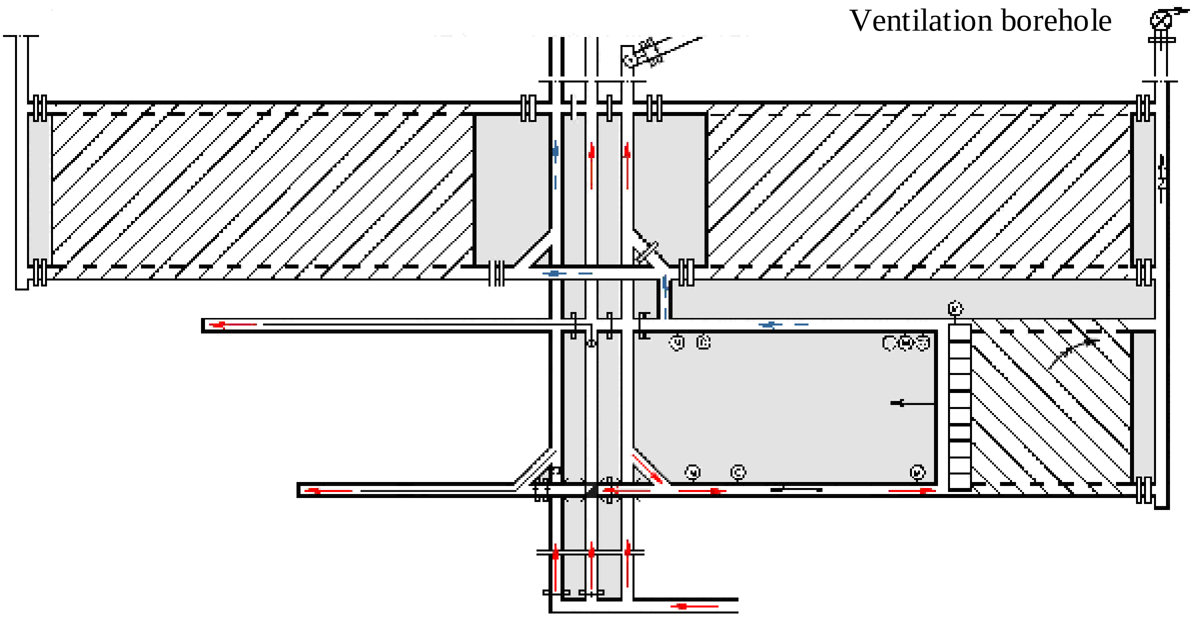


Fig. 1-4: Scheme of a ventilation plan with ventilation borehole in the right upper corner. red arrow for ventilation air (Source: SUEK)

1.3 AMM (Abandoned Mine Methane)

The deliberation of methane also occurs in abandoned mines. The quality and the quantity of the AMM varies between the locations, whereby the methane originates from two sources:

- Desorption from the coal und the surrounding strata, just like in active mines. Compared to active mines this desorption is very slow, as the stress from the strata remains the same in abandoned mines.
- Methane production caused by microbiological processes in abandoned mines[1]. The part of the production is not verified yet.

The gas quality of AMM is usually changing very slowly. Therefore the engines can reach up to 7 500 h per year operation time.

An example for the production of AMM is the Ruhrbasin in Germany. AMM is produced there in many old mines and some plants for CMM utilisations were implemented. The data for methane utilisation in this region in 2008 are given in Tab. 1-1.

[1] "The results obtained in an ongoing BGR research project so far show that the German coal gases are a mixture of thermal and microbial methane. Thermal methane in the Ruhr Basin has an age of around 300 Ma. Microbial methane might be by far younger." [2]

Tab. 1-1 CMM utilisation in Nord Rhein Westfalen 2008 [3]

Type		Abandoned Mine	Active Mine	In total
Module CHP	Pieces	99	29	128
Installed Power	MW	128	42	196
Power Production	MWh*10 ^{3}	642	201	843
Heat production	MWh	25	54	79
Emission reduction t CO_2 eq.				3,700,000

Gas collection from abandoned mines is possible, if a connection between the ground level and the old underground mine exists. It could be an old shaft, a pipeline in a sealed shaft, or a new borehole.

In former times the shaft of a closed mine was often filled with stones and rubbish. Later, the shafts were filled with stones and concrete. During the past 25 year, old pipes in Germany, which where installed in the shaft, have been or are used as degassing pipes. These pipes are connected to one or more levels in the mine. The released gas can be in that way exhausted into the atmosphere as long as the water level doesn't reach the bottom of the pipe.

Fig. 1-5 shows an example for a degassing pipe in a filled shaft. The shaft is filled with concrete in the upper part of the shaft, but the old floor levels are still open and connected to the shaft. The gas can flow to the unfilled part of the shaft and be removed out of the mine through the degassing pipes, which are connected to the ground level.

Fig. 1-5 : Example for a degassing pipe in a filled shaft
Source: A-TEC

in many cases there exists no connection between the mined underground space and the ground level. In those cases a drilling of a borehole into possibly voluminous underground infrastructure is needed, where the gas can be sucked from. If the underground tunnels of the mine are still open, they can be used as a gas collecting system which makes possible to collect the gas from some distance from the extracting point.

Degassing of abandoned mines is often also necessary from a safety point of view. Diffuse emissions of methane from abandoned mines could otherwise take place causing a significant danger for the people living in this area. The Ruhr Area in Germany and the Ostrava region in Czech Republic are examples regions, in which uncontrolled release of methane caused significant hazards for the residents. Therefore special degassing stations were installed in these regions for safety reasons.

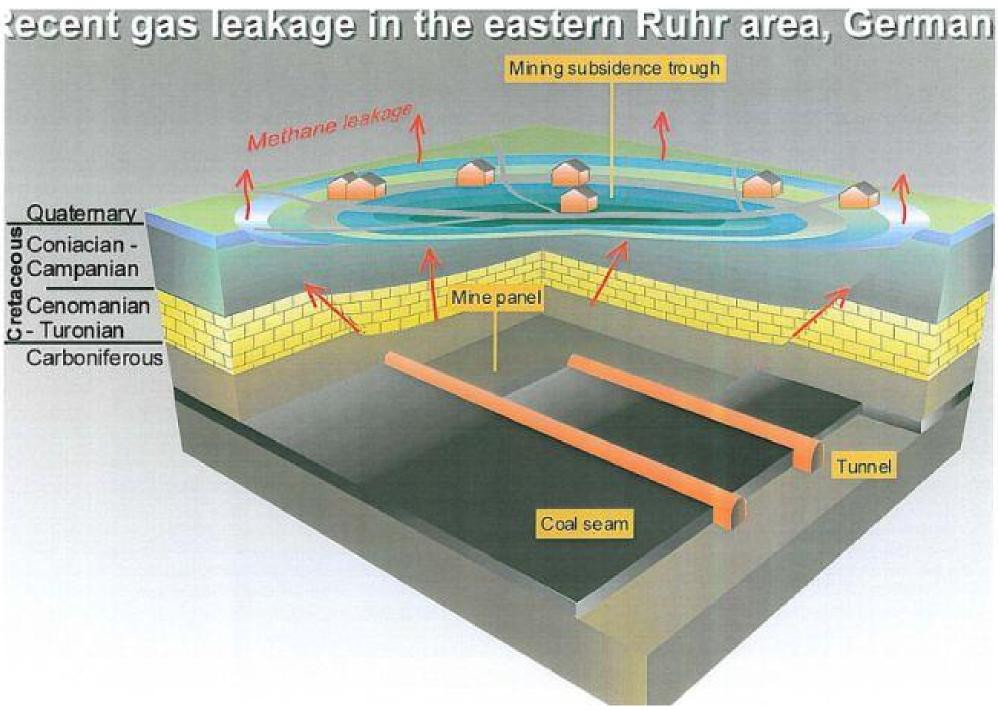


Fig. 1-6 : Diffuse Methane emissions [4]

2 Engines

2.1 Introduction for CMM engine systems

Internal-combustion (IC) engines are able to accommodate to gas streams with a wide range of methane concentrations. Some CMM sources are mixed with air or with inert components like N_2 and CO_2, especially in gob gas. The size and generation capacity of an IC engine varies in a quite large range. Typical CMM powered engines have a capacity between 250 kW and 5000 kW. The gensets smaller than 2000 kW per unit are mostly installed in containers.

In principal a genset consists of the combustion engine, a generator, the coupling, a base frame and an elastic mountings arrangement. The engine and generator are rigidly mounted on the base frame. This unit is used as a combined heat and power (CHP) to generate electricity and heat.

The specifications for individual engines vary depending on the gas components and on the construction. Standard IC engines can run on gas with a methane concentration down to 40% methane in the entrance gas. If the content of methane is less than 40% specific engines have to be used, which can operate with methane concentrations down to 25%. It is important to adjust the correct ratio of O_2, CO_2 and N_2 in order to gain a useable gas mixture. CO_2 and N_2 act like a fire extinguishant. On the other hand oxygen is essential for the combustion but utilisation of this gas mixture with high oxygen levels is very difficult and exceptional.

The mixture-system, as a crucial subsystem of the genset, prepares an air-methane mixture with a methane content of about 7 % in the mixture, which is able to be burned in the cylinder afterward. It has to work on quick response, so that the changes in the gas composition can be considered, due to avoid damage of the engine.

The mode of operation depends on the local conditions and for CMM fuelled gas engines especially on the available gas volume. An efficient operation of the gen set is possible with loads higher than 80. The minimum of 50% is desired due to avoid of damages.

2.2 Components of CMM Gensets

The main part of a CHP module is the engine supported by the following additional components:

- cooling water heat exchanger
- exhaust gas silencer
- exhaust gas cleaning system

- fuel tank or gas supply
- lubricating oil supply
- control & monitoring system
- optional exhaust gas heat exchanger
- generator
- container

Each of the components has a function in the system and is jointly responsible for the correct operation of the gen set:

Cooling water heat exchanger

The explosions in the cylinder cause a drastic increase of pressure and temperature. The pressure is used to turn the crankshaft and the heat has to be discharged to ensure acceptable material temperatures. The waste heat is transported by cooling water from the engine to the a air cooled heat exchanger. As the heat is in range 70-90°C it is also usable for e.g. district heating.

Exhaust gas silencer

The exhaust gas causes big noise emission and in many cases, depending on the local conditions, installation of an exhaust gas silencer might be necessary.

Exhaust gas cleaning system

Exhaust gas cleaning system in CHP systems are necessary to reduce CO emissions. As CMM normally doesn't contain catalyst poison, catalytic systems are applied. In rarely cases e.g. abandoned mines H_2S can be in the gas, but its concentration is low and do not harm the catalyst.

Fuel tank or gas supply

Whilst gas – diesel – engines use a fuel tank for gasoil, the gas (CMM) is supplied from the gas compressor station, which should deliver CMM with a constant pressure. To ensure a proper operation of the engine, liquid water has to be removed from the gas. Moreover appropriate measures have to be taken to avoid condensate formation.

Lubricating oil supply

Lubricating oil has to be changed several times per year. Therefore tanks for new and for used oil are installed on the site and connected to the system, due to make an automatically changes possible.

Control & monitoring system

A computer based control and monitoring system is responsible for the optimised operation of the genset inclusive all subsystem and components, as air mixer and pressure stabilizer. The frame condition is set by the operating staff.

Exhaust gas heat exchanger

The heat of the exhaust gas can be used by means of a heat exchanger. Its installation is not necessary for the normal engine operation and only useful if those energy amounts can really be utilised.

Generator

The generator, linked to the engine produces electric power with voltage harmonised with the electric grid. For systems up to 2000 kW the generator mostly delivers 400 V, which can be converted to higher voltages of the grid by transformers. If all CPH units of the same operator have the same voltage easy changes between installation places is possible.

Container

Many CMM fired engines are installed in a semi-mobile frame, which is often a container and can be moved/relocated with lorries (see Fig. 2-1). Only the gas and power connection has to be done on site.

Fig. 2-1 : Containerised gas engine 1,3 MW_{el}
Source: A-TEC

2.3 Gas – Air - Mixture

The composition of the gas – air – mixture is at every time essential for a high operation efficiency and a long life time of the engine. In modern gas engines the control system checks many parameters (e.g. cylinder and exhaust gas temperature) continuously, as they are indicators for the correct adjustment of the gas – air – mixture.

CMM compared to natural or sewage gas and biogas as fuel makes different demands on the control unit. The reason is its changing composition and the necessity to adjust the gas-air-mixture´s quality.

CMM from active mines can are methane – air – mixtures of about 30% methane in air. In consequence the dimensions of pipes, valves and accessories has to be adjusted for the different volume of fuel gas while the oxygen content of the CMM has to be considered in fixing the CMM – air – mixture. The mixing system has to work for the whole power range with possible big fluctuations of fuel gas volume in time.

The situation in the case of CMM from abandoned mines is different, as the gas is usually not a mixture of methane and air but of methane and inert gas. The mixture often contains CO_2 which acts as a fire extinguishing substance and limits the combustion of methane. A combustion of a gas source with low methane concentration (< 30) and high CO_2 concentration (> 15%) might be so slow, that this gas is not useable as fuel for gas engines.

2.4 Utilisation of engine waste heat

During operation gas engines produce waste heat which has to be dissipated. There are four main heat sources:

1. *Radiant heat from the engine surface*.
   This heat has to be dissipated by room ventilation.
2. *Heat from the compressed fuel gas behind the turbo charger.*
   In most cases this heat is transferred to a special cooling circuit. Due to its low temperature level of the cooling circuit (30 °C - 45 °C) an use for heat supply is not possible.
3. *Heat from the motor cooling circuit.*
   This circuit usually works at a temperature level from 80 °C to 95°C and comprises 25 % to 50 % of the fuel energy. Temperatures up to 105 °C are possible in some special system configurations. However, they are unusual and might cause technical problems, which could reduce the life time of the engine.
4. *Heat of the exhaust gas*
   The heat of the exhaust gas with up to 500°C can be captured by a special exhaust heat exchanger, designed individual for the local specification. In times when no heat is needed by the user, the heat has to be cooled down or the heat exchanger has to be protected against the hot exhaust gas.

Depending on the local conditions, the total efficiency of the engine system can reach more than 85%. An engine without heat production has usually an efficiency of about 37 % in the year average. The utilisation of the waste heat can contribute to more than 50% utilisation of the fuel energy. However, in most cases only a small heat portion is used, as the CMM capacity is much higher than the needed heat amount.

2.5 Further reading on gas engines

1. ATEC "Technical equipment for coal mine suction and utilisation, Combined power and heat systems", url: http://ausruestung.atec.de/englisch/bhkw_pics_eng.htm (2009- 11-11)
2. Shengdon New Energy Technology Co., Ltd, "Gas generator Cole Mine Methane Gensets" url: http://sd-generator.en.made-in-china.com/product/eqdQDRbUgmHi/China-Gas-Generator-3-Coal-Mine-Methane-Gensets-500GF1-2RW-.html (2009- 11- 11)

3. GE's Energy; „GE Jenbacher Gas Engines“
url: http://www.gepower.com/prod_serv/products/recip_engines/en/index.htm
(2009-12-3)

3 Boilers / Burners

3.1 Description

In a boiler the chemical energy is converted to thermal energy. The main part of a boiler is the fire box with a burner located inside. All around the fire box pipes or box sections are installed, in which a liquid (mostly water) is heated up by the thermal energy of the combustion.

There are two ways for categorising of boilers:

- by the kind of fuel which is used for the combustion
(main groups: natural gas, oil, wood, biomass, other combustible materials: for example waste gases in chemical industry)

or

- by the product as heated water or steam.

The production of heat or steam in boilers is the eldest and best known utilisation of CMM, whereas special burners use CMM as fuel. These CMM burners are also used in some other applications like coal dryer, ventilation air heater or as industrial heaters.

For using CMM as a fuel in boilers gases with a wide range of concentration can be utilised. Safe operating systems for methane contents from 25% up to 100 % are available. On some locations utilisation of gases with methane concentration down to 20% are allowed.

3.1.1 CMM as additional fuel

Especially in coal fired power plants with CMM production nearby, CMM can be used as additional fuel in boilers. As the energy amount of the used CMM is small compared to the coal consumption, no special regulation is needed for the burning of the CMM in the big fire box. The safety installations depend on the local situation. In most cases a special regulation of combustion air flow is not required.

However, even if the co-firing of CMM is a simple possibility for CMM utilisation it is only reasonable, if the distance between the CMM extracting point and the power plant is acceptable.

3.1.2 CMM as mono fuel

In the past 20 years CMM has been used as mono fuel in boilers. Special safe burner systems are used instead of natural gas burners in gas boilers. Furthermore there are burners available for use of CMM as normal fuel and oil as secondary fuel. Sometimes a modification for fuel switch is not necessary. This kind of burners and boilers are often used on coal mine sites in Germany (see Fig. 3-1)

Fig. 3-1: CMM – Oil Burner
Source: A&/S Waermetechnik GmbH

In many mines especially in Eastern countries coal fired boilers are retrofitted with a gas burner system. The grate is covered to protect it against the flame heat. In most cases a modification of the air inlet is not necessary.

3.2 Gas – air – mixture in CMM burners

Precise control and regulation of gas – air – mixture in CMM burners is necessary to ensure complete gas combustion, as well as a low CO content in the exhausted gas and a good efficiency of the overall system.

The burner load is regulated by the energy demand. However, the capacity of gas consumption is limited to the maximum gas volume, which can be charged to the burner. The different CMM qualities (CH_4-content) make specific demands on the control and regulation system. For example: If the content CH_4 of the CMM can range between 25 % and 60 %, the cross sectional area of the gas flow channel has to be dimensioned for gas with 25% CH_4 to reach full load. When the same volume of CMM with 60% CH_4 flows through this channel, the load would reach values of 240% as the gas contains more than the double energy compared to the CMM with lower CH_4 contents. Therefore maximum volume flow of CMM with 60 % CH_4 has to be limited to 42% of the maximum possible volume flow for security reasons.

The proper function of the adjustment of gas and air is controlled through the measurement of oxygen concentration in the exhaust gas, which should be between 1.5% to 3 % at every time.

3.3 Specifics for CMM burner installations

The most burner systems are designed for natural gas. Special attention has to be paid to the differences between natural gas and CMM to obtain a good and save working system. Three aspects are important:

- the change of calorific value (changing volume, density and CH4-content),
- existence of water and steam in the gas and
- pollution through dust in the gas.

In opposite to natural gas burners ,air valve and gas valve should not be fixed interlinked due to the changing calorific value of the CMM (refer to chapter 0). In modern constructions an open combination or electronic combination is used for the regulation of the gas valve and the air one. Through oxygen measurement in the exhaust gas a proper control is possible, provided a solid gas analyses for CH_4 and O_2.

The existence of water and steam in CMM gas do not necessarily require a drying of the CMM before burning. However, it has to be ensured that the water in the gas is not a reason for failures in the burning system. Possible condensate has to be separated and led away of the pipe. Moreover all used installations have to be dimensioned for wet gas. Especially the material from the gasket of the valves has to be qualified for these conditions. If ordinary gaskets for dry gas are used, they will swell in contact with water. Following the valve cannot work any more and the burning system fails.

Analogue the installation should be able to deal with some dust in the gas. To prevent failure of the burner the installation of a dust filter in the beginning of the burner installation is needed. The degree of pollution and necessity for filter cleaning can be determined by measurement of the regarding pressure difference. The installation of a shutoff valve is advisable to allow filter cleaning by the staff.

Fig. 3-2 : CMM burner with subsystems,
Source: A&S Waermetechnik GmbH

3.4 Further reading on boilers / burners

1. Canadian clean power coalition, "How a Coal-fired Power Plant works" url: http://www.canadiancleanpowercoalition.com/Customer/ccpc/ccpcwebsite.nsf/AllDoc/9D9A829BA5468A3A8725697B007D2DA2?OpenDocument (2009-12-3)
2. Indtex Boiler Pvt. Ltd url: http://indtex.en.ec21.com/
3. L&T MHI Boilers Pvt. Ltd. url : http://www.plm.automation.siemens.com/ko_kr/about_us/success/case_study.cfm?ComponentTemplate=1481&Component=74088
4. TT Boilers, „Steam boiler – heavy duty classic 3-pass steam boilers", url: http://www.ttboilers.dk/Damp.htm (2009-12-3)

4 CMM flaring

4.1 Description

Flaring is a controlled combustion process in which the combustible material to be flared is piped to a remote, usually elevated location, and burned in an open flame in the air. The specially designed burner tip and supporting equipment as auxiliary fuel feed system and steam or air mixing device makes nearly complete (>98%) destruction efficiency possible. The usual methane concentration of the utilised gas is 20% and above. The combustion process in a flare is controlled through the flame temperature, combustion zone residence time, the mixing turbulence of the gas stream components to complete the oxidation reaction and available oxygen for free radical formation.

CMM flaring can be performed in either open or closed systems (Fig. 4-1), and the technique is similar to that implemented in the oil and gas industries. This method of methane disposal is relatively cheap compared to the extra costs connected with power generation infrastructure or incorporating recovered methane into a region's natural gas pipeline network. However, the big disadvantage of this process is the heat energy which can not be recovered.

Closed Flare

Open flare

Fig. 4-1 : A closed and an open flare

As mentioned above flares can be closed or open, whereas a closed (thermal oxidizer flare) flare offers more benefits compared to an open (utility) one. The closed flare consists of a vertical, refractory-lined combustion chamber that effectively eliminates any visible flame. As the flame is enclosed, there is no thermal radiation from the flare at ground level, ensuring safety of work in the surrounding. Moreover, the closed design reduces noise associated with the flare. The burner is located at ground level and is designed to ensure the biggest destruction efficiency under maximum burner turn-down. The combustion air enters the combustion chamber from below the burner by automatically controlled louvers or dampers.

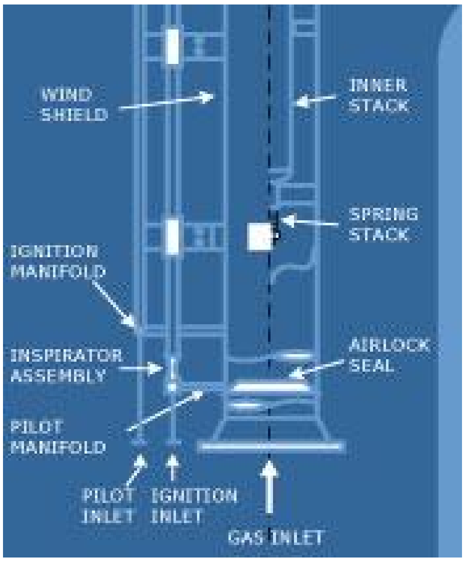
The advantages of a closed flare are

- the not visible flame,
- the large volume flows to be dealt with,
- a better burner/flame control and
- a burning of all flammable gas components.

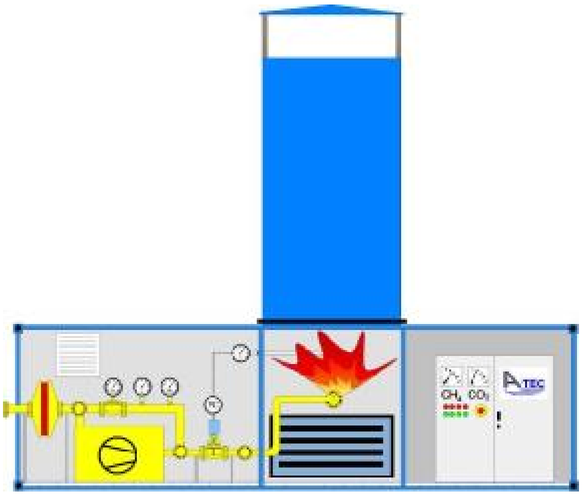
Unfavourable are the relatively bad portability and higher overall costs.

A flaring system generally consists of the following major components and subsystems (Fig. 4-2):

- Collection piping within a unit (including a mix of pressure reliefs and vents)
- Components of a flare to the site
- A liquid separator to keep away water drops from the gas stream
- A flare stack with flare tip
- A fuel gas system incl. pilot burners with ignition
- Controls and instrumentation
- Compressor to feed the flare (option)



Closed flare system



gas compressing and closed flare system

Fig. 4-2 : Major components of an enclosed flare system Source: A-TEC GmbH

The flare components have supporting role and are necessary or optional for the operation:

Liquid separator for keeping away of water drops from the gas stream

In some degassing systems the CMM contains water drops. These may be caused by the water ring pumps or by the condensation of moister in the coal mine gas. This water should be separated due to avoid damages in the hot parts of the flare and special burner parts.

Flare stack with flare tip

The flare stack for burning CMM is mostly a closed system to guarantee a very good destruction of the methane. The enclosure covers the whole flame and is big enough to allow a complete combustion of the CMM.

Fuel gas system incl. pilot burners with ignition

There is priming needed for start of the combustion in CMM flares. It is mostly a starting ignition plug with power delivered by the switchgear. In most cases CMM is used as supporting burner fuel, so that a special compression is not needed.

Especially for CMM with very low calorific value a special supporting fuel is needed. If the location is not connected to natural gas supply, propane or butane (or acetylene) in compressed gas cylinder can be used to have an ignition flame to start the main burners.

Controls and instrumentation

The switchgear contains the whole measuring and control technology to guarantee a save burning process. Especially the control of the flame and the flame temperature is very important and has to be done continuously. In a case, where flame dies down, by too high or too low flame temperature the feeding of fuel (CMM) has to be stopped immediately. Discharge of CMM into a hot combustion chamber without ignition may lead to gas explosions. Too high temperature may cause damages of the materials in the combustion room. The burning temperature should be between 800 °C and 1200 °C, whereby the materials and the isolation should be stable for this temperature level.

Compressor for feeding of the flare (option)

Compact stations can flare the CMM independently from a central degassing station. A compressor is included in the system to extract the gas from underground and feed it to a burning system in a flare. In this case the switchgear and the measuring and control technology has to deal with both: the gas extraction and the gas burning. An example of a closed flare with a compressor is shown in Fig. 4-3.

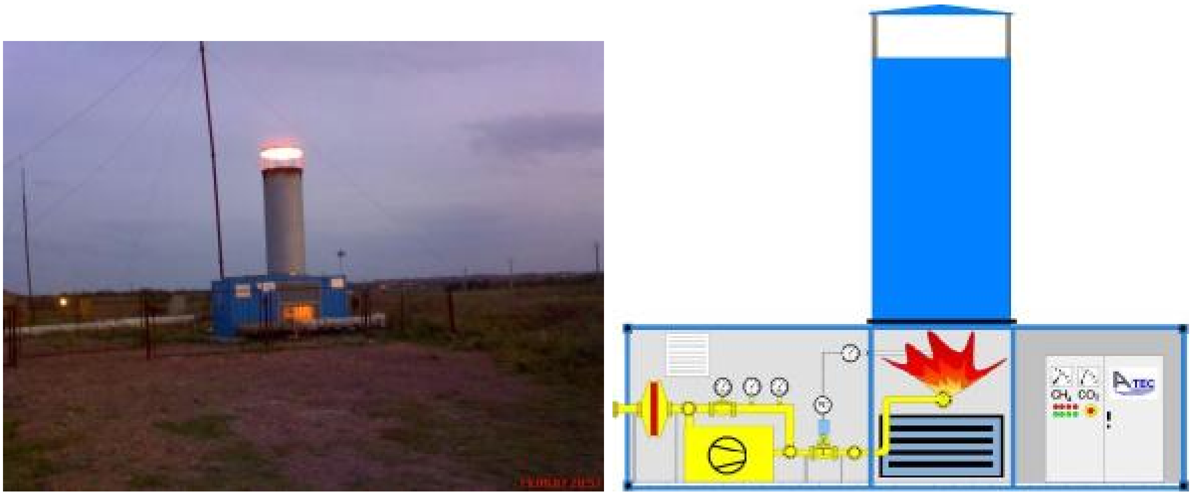


Fig. 4-3 : Compact station for degassing and flaring
Source: A-TEC GmbH

The advantages of flare plants have to be weighted against the main disadvantage of impossibility to use the thermal energy of the combustion:

- Flares are a low cost technology with a short manufacture and installation lead time.
- Flares are simple, low cost and reliable in the operation. Gas flaring offers a very high potential for significant GHG reduction by transferring the methane in CO_2.
- Flares require only low maintenance.
- Flare units can be installed, operated and maintained at a significant cost reduction on conventional utilisation systems.
- Flaring is the ideal option where time constraints, low cash flows and low electricity price might be significant barriers for power production.
- Flares can automatically be controlled.
- Distance (i.e. internet) remote monitoring and control is possible.

4.2 Examples of use

- 11.08.2009 a JI-Project in an active mine shaft in a mine in Saarland in Germany was started up by Evonik New Energies. The expected activity level amounts to 39,200 t CO_{2eq} during the period from 2009-2012 [5].
- In October 2007 the first flare plant was started up in Molodogvardeysk in the Ukraine. The flare was delivered by A-TEC Anlagentechnik GmbH with the capacity for destruction of over 2800 t methane per year [6].
- In the mine 22 Kommunarskaya a flare starts up by ECO-Alliance. The expected activity level amounts to 40.000 MWh/a. Start operation Jan. 2009 [7].
- Rivne Landfill, proposed by the Renewable Energy Agency. The ambition of the reduction amounts to 20.000 mtCO_2eq per year [8].
- Russia: North- Danilovsk oil field, Khanty- Mansiysk Okrug, the ambition of the reduction amounts to 814.860 mtCO_2eq during 2008-2012 [9].

4.3 Further reading on flares

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2. Neil Butler, “Coal Mine Methane Drainage and Utilisation”, Methane to Markets, Beijing, 30th October 2007 http://www.methanetomarkets.org/expo/docs/postexpo/coal_butler.pdf
3. ATEC, “Technical equipment for coal mine gas suction and utilisation, Mobile gas compressor and flare system (KGUU)” http://ausruestung.atec.de/englisch/fackel_varianten_eng.htm (2009-12-03)
4. Hofstetter “HOFGAS – CFM4c, The Coal Mine Methane Flare” http://www.hofstetter-uwt.ch/?file=Products_Coalmine_CFM4c.htm (2009-12-03)
5. “Benefits of an Enclosed Gob Well Flare Design for Underground Coal Mines” EPA 430-R-99-012; August 1999 http://www.epa.gov/cmop/docs/022red.pdf (2009-12-03)
6. Robert E. Schwartz and Dr. Shin G. Kang, “Flare System Design – What is important?“ http://johnzink.com/products/flares/pdfs/tp_important.pdf (2009-12-03)

5 LNG

5.1 Characteristics of LNG

LNG – Liquefied Natural Gas – is a clear, odorless, colorless, non-corrosive and non-toxic, cryogenic fuel which is composed primarily of methane and be stored below methane's boiling point, -161ºC, at near atmospheric pressure. At this temperature and pressure the methane exists as a liquid. Depending on the composition of the feed gas, the volume ratio between the gaseous state and the liquid state is about 600:1. This makes LNG suitable for storage and transportation in large quantities. The heating value of LNG is estimated to a lower heating value of about 21000 MJ/m^3.

LNG is very efficient as energy carrier and so there are some advantages to use it.

- Environmentally friendly - methane, a dangerous greenhouse gas, is captured and processed instead of vented to the atmosphere.
- Cost-effective fuel source - processed gas powers onsite equipment or can be sold to nearby gas pipelines.
- Potential for carbon credit trading as a qualified emissions reduction.

5.2 Processes of coal mine methane (CMM) upgrade and liquefaction

The properties of CMM depend on the coal bed source and the method of its recovery. They may vary over time and depend on the conditions of its extraction. The typical components of CMM include methane, carbon dioxide and nitrogen. Substances as hydrocarbons of longer chains, water vapor, oxygen, hydrogen, carbon monoxide, helium, hydrogen sulfide, chlorine hydrogen, fluoride hydrogen, ammonium and mercury may occur in smaller or trace amounts.

Similarly as in the case of other mine gases e.g. natural gas, CMM requires purification before any application or processing including liquefaction to remove the undesired substances.

5.2.1 CMM purification

Removal of dust and stray oils

All CMM-to-LNG plants have to have inlet separators to remove dust, compressor oil and any entrained water or hydrocarbons. Liquids and solids are removed by gravity separation-coalesced on filter media or mesh pad. Compounds which can freeze in LNG must be reduced.

Dewatering

Gas extracted from coal beds usually contains water vapor. Its content in CMM may pose serious problems in low-temperature (cryogenic) gas processing installations due to the condensation and formation of ice traps and crystalline hydrocarbon hydrates which may block the installation.

Therefore gas must be dried before further processing. In the case of high-methane content gas liquefaction, the drying must be very deep to the level <1 ppm.

H_2S and CO_2 removal

Hydrogen sulfide as well as other sulfur compounds e.g. mercaptans must be eliminated from CMM due to the following reasons:

- The toxic properties of hydrogen sulfide disqualify gas with H2S content for household use.
- Hydrogen sulfide causes intensive metal corrosion. Therefore its presence in the gas results in damages of the fittings and the gas processing installation.
- The purify specifications for gas application for chemical syntheses regarding hydrogen sulfide are very high as it is toxic for the catalysts. Moreover, the presence of H2S in the raw material may affect the quality of the obtained chemical product.

The above reasons indicate that hydrogen sulfide removal from high-methane gas is a technological necessity.

If contained in the gas, carbon dioxide is removed together with hydrogen sulfide. In the case of low temperature gas processing, there is a risk of CO_2 solidification which may cause stoppage in the fittings

Degasolination

C_3+ hydrocarbons are eliminated from gas by degasolination. The outputs: liquid gas and light benzine (called gasoline) are valuable fuels and materials for chemical syntheses.

Denitrification

Gases with high nitrogen content represent much lower calorific value then low-nitrogen gases. Therefore nitrogen as gas component should be reduces as far as possible.

Oxygen management - thermal oxidation

This type of oxygen removal system is based on catalytic combustion of oxygen. The process operates below the auto-ignition temperature of methane at the process pressure.

The reactor contains the catalyst and is designed to have a sufficient volume of catalyst necessary to burn the amount of oxygen required. When the oxygen content in feed gas stream is high, the oxygen in the feed gas must be diluted to prevent overheating and damage to the catalyst due to the exothermic reaction. The catalytic reaction oxidises methane and produces water and carbon dioxide. Following the gas flows through two heat exchangers. Condensed water is removed in a separator and the gas exits the oxygen removal unit.

5.2.2 Liquefaction of the mine gas

The choice of the gas liquefaction technology depends on the desired efficiency performance of the installation, gas composition (content of CO_2, H_2S, N_2, heavier hydrocarbons) and its pressure. There are three hydrocarbon gas liquefaction technologies presented in the literature sources:

- classical cascade cycle;
- auto refrigerant cascade cycle (using mixed refrigerant of hydrocarbons extracted from the liquefied gas);
- decompression cycle with a turbo-expander unit.

Classical cascade cycle

The classical cascade process consists in cooling the natural gas in three refrigeration cycles. As refrigerants propane, ethane and methane are used. Feed gas stream purified from water and CO_2 content flows under the pressure of 3-4 MPa into a train of cryogenic exchangers. It is cooled in the three successively lower refrigeration levels forming a cascade train.

After decompression each of the refrigerant streams (propane, ethane, methane) undergoes a successive, several-stage compression to increase the energy savings of the process. Low energy consumption is the primary advantage of the classic cascade method. About 0, 5 kWh is used to liquefy 1 m^3 of gas. All these requirements result in high operational costs of the installation.

Auto refrigerant cascade cycle

This method is a classical cascade technology. However, only one compressor and one refrigerant are applied. The refrigerant is a mixture of hydrocarbons extracted from the C_2+ fraction condensed from its methane fraction.

A mixed refrigerant cascade train with propane cycle pre-cooling consume about 0,6 kWh/kg LNG. It is by several per cent more than the classical cascade process. Another strong point of this system is the production of the circulating refrigerant directly from the liquefied natural gas.

Decompression cycle

The decompression cycle based installations for hydrocarbon gas liquefaction perform according to the principle similar to the classical Joule-Thompson natural gas liquefaction method and installations for liquid oxygen and nitrogen production by cryogenic air fractionation. Gas liquefaction by decompression cycle is characterized by low efficiency; however, it is simple and requires relatively low investment outlays.

The key element of the process is a turboexpander, in which 85% of the gas is decompressed and cooled to cryogenic temperature.

Decompression cycle trains are usually built in locations where the energy needed for the process is cheep as the energy demand of these installations is much higher than in cascade cycles.

The most popular expander system – reverse Turbo-Brayton cycle is presented in figure 5-1.

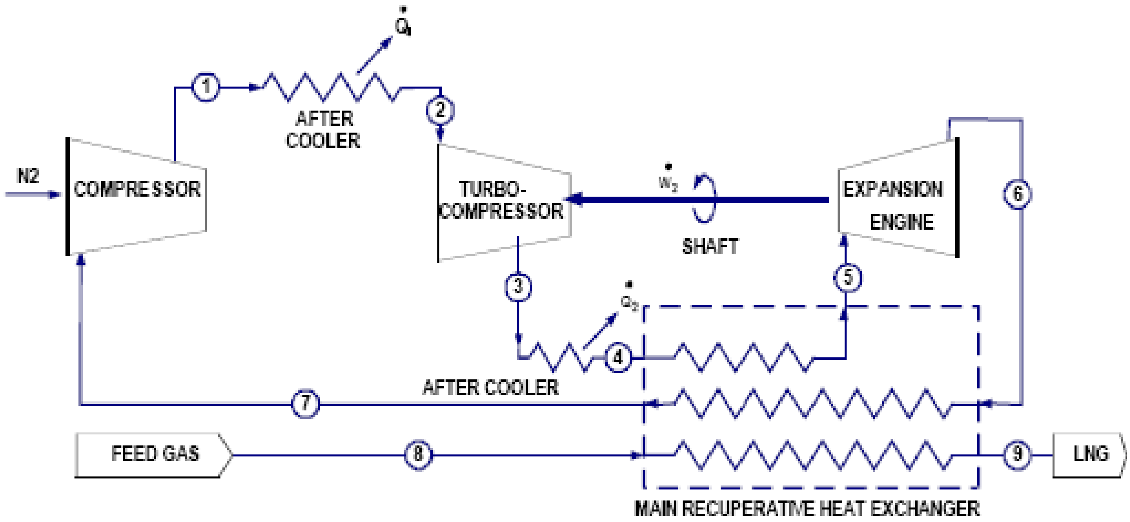

Fig. 5-1: Reverse Turbo-Brayton cycle refrigerator.

5.3 Examples of Use

- Snøhvit, Norway: The project is an example for offshore LNG utilization and starts in the fourth quarter of 2007. The capacity of the LNG venture is 4.3 million tonnes per annum [10].
- Krupinski Coal Mine near Katowice, Poland: Planned for conversion of10000 Gallons of LNG per day [11]
- Kwinana LNG Plant, Western Australia: Since August 2009 the plan was started up by Wesfarmers Energy which liquefied 175 t LNG per day [12].

6 VAM Utilization

As mentioned in chapter 1.1 Ventilation Air Methane has a very low methane concentration. Thus it is very difficult to be use or to be utilize. VAM contains the biggest amount of methane which is released by coal mines, but up to now there are no big scale technologies for its destruction or utilisation. However, currently a lot of research activities are executed regarding thermal oxidation as a new technology to utilise VAM. Some demonstration projects are running or will be started in the future.

Especially in the frame of JI projects it is very interesting project activity for generation of emission reduction units by restructure of VAM. Moreover, the methane is released in the vicinity of the ventilation shaft. This location is expected to have a long life time. So installed plants do not have to be moved, if the digging area changes in the underground.

6.1 VAM utilization by thermal oxidation

Even if methane concentration of VAM is quite low (typically 0,3 to 0,7 percent), the volume of air that ventilation systems move is so big, that they actually are the largest source of methane emissions from underground coal mines. Basing on the experience of exhaust air treatment (e.g. air with solvent damp) a technology for VAM utilization was developed: flow-reversal oxidation.

6.1.1 Flow-reversal oxidation – operating principals

The basic operating principal underlying flow-reversal regenerative oxidizers is rather straightforward (see: Fig. 6-1). Each oxidizer unit comprises a bed of heat exchange material with a preheating system (e.g. electric heating element). Ducting conveys the gas to be oxidized (VAM in this case) into the oxidizer core. The heat exchange material typically comprises ceramic pellets with a high surface area-to-volume ratio. The oxidizer also has a system of valves and dampers that direct the VAM flow across the bed. To start up the system, the preheating system raises the temperature of the heat exchange material in the oxidizer bed to or above the auto-oxidation temperature of VAM (> 800°C), at which point the preheating system is turned off and VAM inflow is initiated. The methane oxidizes when it reaches the preheated bed, releasing the heat of combustion. This heat, in turn, is transferred to the bed, thereby maintaining its temperature at or above the temperature necessary to support auto-thermal operation. It should be noted that the oxidation process is flameless and, following the initial bed preheating, requires no auxiliary fuel so long as adequate inflow methane concentrations are maintained.

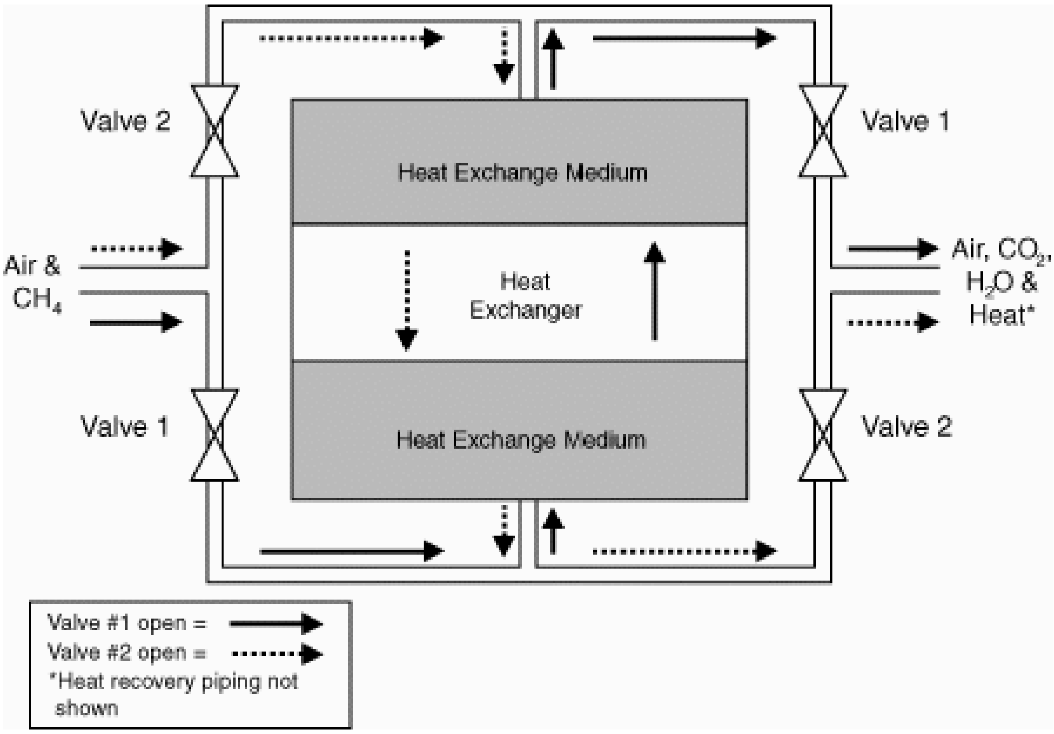

Fig. 6-1: Flow-Reversal Oxidation

If the inflow of ambient-temperature ventilation exhaust air is maintained in only one direction, the heated area of the bed would migrate across the bed in the direction of flow until the heat essentially is blown out of the bed. If that happens, bed temperatures would no longer be adequate to sustain auto-thermal operation, and the system would cease oxidizing subsequent VAM inflows. To preclude cooling of the bed, dampers and valves redirect the flow of incoming ventilation exhaust air from one side of the bed to the other, typically on a timeframe of every two or three minutes. This flow-reversal process, which is managed by a programmable logic controller, maintains the hot area of the bed in the middle of the oxidizer, where it is available to support oxidation of a constant stream of VAM over time.

However, there are a few drawbacks that show the inefficiency of the oxidizing process. The first case is the decrease in pressure during the VAM flows through the oxidizing chamber. There is also a lot of dirt in the flow of the VAM that causes contamination of the filling material and the valves. Another problem is the not constant heat dispersion. The dispersion effuses in a parabolic profile. So, in the middle of the chamber it is warmer than in the peripherals.

The VAM from the ventilation shaft has to be compressed to compensate the pressure losses in the air – methane – mixture filtration and oxidation area. This additional pressure can't be produced from the ventilation fan.

All operating VAM projects to utilise CMM are in a research or a demonstration phase. At the moment notably two companies are active in developing VAM technologies. Moreover a third company is developing a VAM utilisation, but have not demonstrated its technology yet. Nearly all information is originated from these companies. So in the following we will describe this technology by using companies' papers.

6.2 VOCSIDIZER® technology developed by MEGTEC Systems, Inc.

6.2.1 Description

The company MEGTEC has been active in research and developing thermal oxidizers for several years. Since the first demonstration done at the Thoresby Mine of British Coal during a few months in 1994, MEGTEC has been developing VAM technology. Currently 3 large size demonstration installations have been in operation for more than a year around the world. One of them is shown in the figure below.

Fig. 6-2: Vocsidizer®
Source: MEGTEC

According to manufacturer's data*"the system is based on a patented combination of emission control and steam-cycle technologies. By using the compact and flameless VOCSIDIZER® regenerative thermal oxidizer (RTO) as an energy source, MEGTEC has made it possible to generate high grade, super-heated steam from a fuel with 0.9% methane content. The steam has the same quality as used at traditional power plants. It is used to drive a conventional steam turbine, which generates electricity that can be delivered to the state grid or directly to the mine."* [13]

VOCSIDIZER® technology developed by MEGTEC is introduced to recovery and utilisation ventilation air methane (VAM) as a kind of energy to generate heat or power. And its successful application at several coalmines in UK and Australia shows its big potential and perspective to be transferred to Chinese coalmines. By using the compact and flameless VOCSIDIZER® regenerative thermal oxidizer (RTO) as an energy source, MEGTEC has made it possible to generate high grade, super-heated steam from a fuel with 0,5%-1,2% methane content.

The unit consists of a single heat transfer bed filled with ceramic media (Fig. 6-3). Plenums (located above and below the bed) can serve either as the inlet or outlet route for process or cleaning air. The direction of air flow from the forced draft fan is controlled by pneumatically operated valves. The dampers will periodically switch position to reverse air flow and allow thermal regeneration of the bed. The bed is initially heated to > 800°C by a grid of electrical heating coils (only during first start-up).

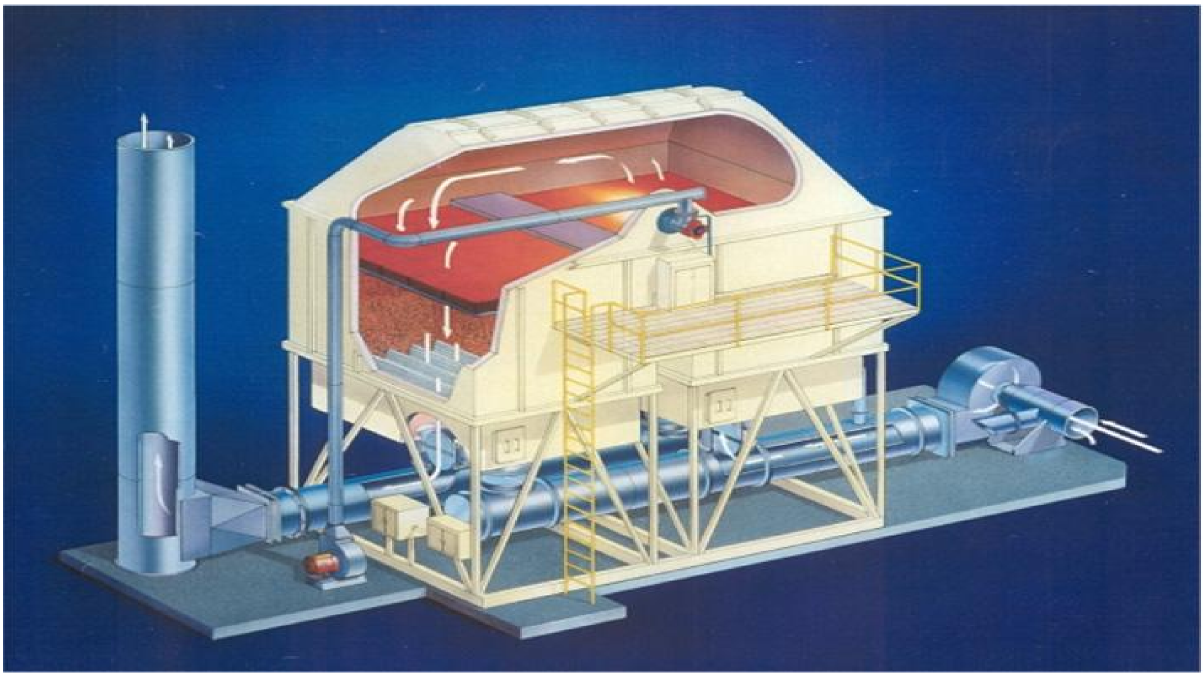

Fig. 6-3 : Vocsidizer® scheme

6.2.2 Examples of use

- West Cliff Colliery, BHP Billiton, Australia:
  VAM Power Plant WestVAMP (West Cliff Colliery Ventilation Air Methane Plant) at Illawarra Coal, BHP Billiton in Australia, located south of Sydney. The installation, patented by MEGTEC, consists of 4 Vocsidizers® integrated into a steam cycle generating high grade, superheated steam designed to suit a conventional 6 MW steam turbine. In full operation since April 2007, with over 96% availability, the installation had by 2009 generated over 500,000 carbon credits traded locally in Australia, and over 80,000 MW of electricity [14].
- VAM Vocsidizer, GaoCheng Mine
  Commissioned in 2008, a single unit VAM Vocsidizer® is processing VAM at the GaoCheng Mine of the ZhengZhou Mining Group in the Hunan Province, People's Republic of China. The installation is utilizing the energy released to generate hot water for miners' showers and for heating of nearby buildings. This is the globally first implemented VAM CDM Project which is registered and formally approved by UNFCCC for the generation of CER carbon credits.
- VAM Vocsidizer® abandoned Windsor mine in West Virginia
  In the USA, Consol Energy in 2007 installed a single unit VAM Vocsidizer® at the abandoned Windsor mine in West Virginia. The abandoned mine gas was injected into a fresh air flow in order to simulate VAM at various concentrations. After 18

months of demonstration and evaluation, CONSOL Energy is planning to relocate the VAM Vocsidizer® to an operating mine

.

6.2.3 Further reading on Vocsidizer

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   url: http://www.minexpo.com/Presentations/Winschel.pdf
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   url: http://www.epa.gov/cmop/docs/cmm_conference_oct08/07_kosmack.pdf
3. H. Lee Schultz, Richard Mattus, De Pere, WI, F. Peter Carothers, " Mitigation of Methane Emissions from Coal Mine Ventilation Air, Western States Coal Mine Methane Recovery and Use Workshop, Grand Junction, Colorado, April 19-20, 2005
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5. MEGTEC information "VOCSIDIZER® - Regenerative thermal VOC oxidation"
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6.3 VAMOX™ technology developed by Biothermica

6.3.1 Description

Another company - Biothermica - has been active in the VAM market for the last years.

Fig. 6-4: Vamox®
Source: Biothermica

Accoring to Biothermica announcement a first installation is already in operation (Fig. 6-4):

"Biothermica announced in April 2009 that its pioneering VAMOX® coal mine methane (CMM) abatement system is fully operational at Jim Walter Resources' mine no. 4 in Brookwood, Alabama. For the first time in America, ventilation air methane (VAM) is being destroyed at an active coal mine, all the while generating bankable carbon credits: Capacity: 30 000 SCFM" [15].

The principles of VAMOX™ operation are shown in the figure below. VAMOX™ converts VAM with concentration range between 0,2% and 1,2% into carbon dioxide and water vapour using the well known principle of regenerative thermal oxidation (RTO). RTO is based on the cyclic reversal of the airflow through multiple vessels filled with heat absorbing media to minimize heat losses during the oxidation process. The VAMOX™ unit is first preheated with fresh air at a reduced flow rate and using a gas burner, a fan forces the mine ventilation air stream through one of the beds which warms the air up to the desired oxidation temperature (addicted to the system). As the temperature increases, the oxidation reaction starts to take place which generates additional heat. The air stream then passes through the oxidation chamber which allows for the complete oxidation of the low concentration CH_4. After oxidation, the stream passes through the other bed which absorbs most of the heat contained in the air. The processed air flow is then released to the atmosphere through the stack. The destruction efficiency of methane contents up to 98%.

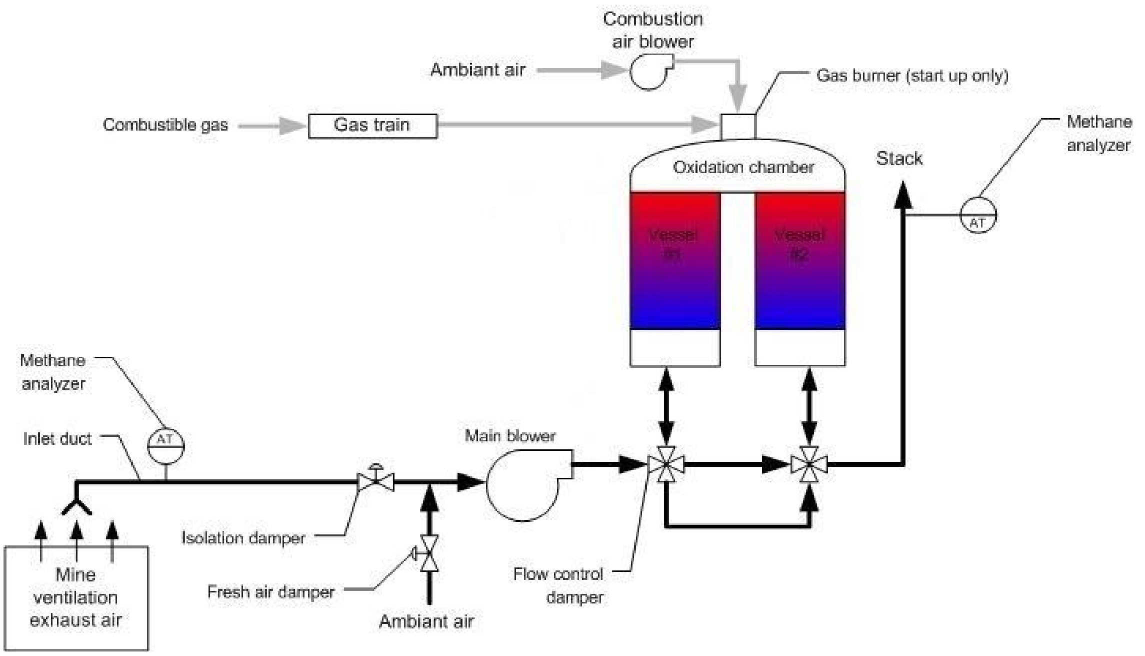

Fig. 6-5: Vamox® principles

Whenever the VAM concentration is above 0,25%, heat can be recovered as hot water or low grade steam. Over the past 4 years, Biothermica has studied the specificities of coal mining operations, heavily invested in R&D and has been actively involved with CMM recovery stakeholders around the world. As a result, VAMOX™ is specifically designed to maximize the performance and profitability of VAM oxidation projects. The oxidation temperature is as low as 800°C.

6.3.2 Examples of use

Jim Walter Resources (JWR) Mines No. 4 and No. 7, USA
Approved by the U.S. Department of Labor's Mine Safety & Health Administration (MSHA), the demonstration system oxidized methane for the first time as originally planned on January 26, 2009.

6.3.3 Further reading on Vamox

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6.4 VAMCAT

6.4.1 Description

VAMCAT is the acronym for »ventilation air methane catalytic combustion gas turbine«, which has been developed and patented by CSIRO (the Commonwealth Scientific and Industrial Research Organisation) with a goal to utilise gases with methane concentrations between 0.3 % and 1.0%.

As shown in Fig. 6-6 VAM is oxidised by using monolithic ceramic catalysts doped with platinum and palladium, similar to those that are commonly used as catalytic converters in automobiles in many countries. The heat which is set free is used to expand gases and the expansion of the gases drives the fans in a turbine in a conventional way, in a normal gas turbine of jet engine.

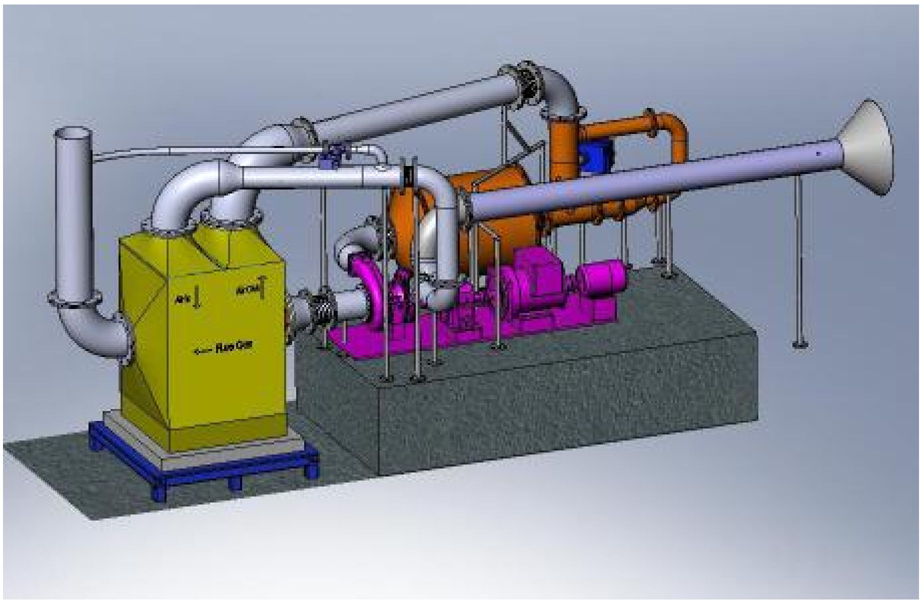

Fig. 6-6: VAMCAT scheme

To date the technology has been scaled to a 25kW demonstration unit.

6.4.2 Examples of use

CSIRO, with the support of the Australian Greenhouse Office and China's Shanghai Jiaotong University and Huainan Coal Mining Group will construct the first VAMCAT pilot-scale demonstration unit at a coal mine in China [16].

6.4.3 Further reading on VAMCAT

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3. Tim McLennan, “New technology to convert China's mine methane emissions to energy”, Radio Australia – Innovations – Summer Series Energy for our Future - Methane Converted To Low Emission Energy, 1st January 2007 http://www.abc.net.au/ra/innovations/stories/s1806573.htm (03.12.2009)

7 Gas Turbines / Microturbines

7.1 Description

Clean and efficient microturbines are state of the art for onsite power generation technology that can use natural gas, renewable or “waste” fuel gases to produce electricity and useful heat. Generally a gas turbine, also called a combustion turbine, is a rotary engine that extracts energy from a flow of combustion gas. It has an upstream compressor coupled to a downstream turbine, and a combustion chamber in-between.

Microturbines are low maintenance efficient clean energy solutions. They are well suited for the smaller source of coal mine methane (30 kW to 250 kW) as they provide a modular approach to generating electricity close to the source gas, making beneficial use of other wise capped or vented methane and can reduce mine ventilation costs. Microturbines are commercially available and are operating at 20% to 35% electrical efficiency for natural gas. Generally they are applicable for methane concentrations in the range from 40 – 100% and are able to convert more than 99% of the methane during operation of the gas turbine. An schematic example of a microturbine is shown in Fig. 7-1.

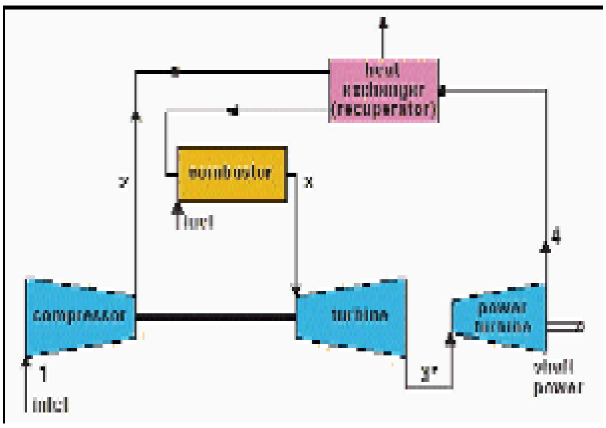

Fig. 7-1: Principles of a gas turbine that employs regeneration (Energy Solution Center) [17]

Commercially available microturbines need a constant caloric value. Microturbines for changing caloric value of CMM microturbines are commercially not available. Moreover, as gas turbines need compressed gas as fuel, CMM has to be compressed from nearly atmospheric conditions to operation pressure (6 to 20 bar). Therefore a compressor station is needed incl. all secondary structure like drying, dust removal and cooling system.

Compared to reciprocating engines, microturbines have a very high power to weight ratio and are smaller when providing the same power rating. Moreover, they move in only one direction causing less vibration than a reciprocating engine and have fewer moving parts. Other benefits are the low operating pressures, the high operation speeds and the low lubricating oil cost and consumption.

7.2 Examples of use

- In Dortmund (Germany) at RAG Mine Gneisenau, a CMM-Turbine was set in operation in 1987 and after some damages and the closure of the mine shutdown several years later. The turbine utilized gas with a caloric value of 4.2 kWh/m3 and operated at a gas pressure of 12,5 bar leading out a power production of 3.285 kWbrutto and 2.672 kWnetto.

- City of Burbank Landfill, Burbank, California
City of Burbank Renewable Portfolio Standard requirement of 20% of power used by Burbank's residents and businesses to come from renewable sources by 2017.

7.3 Further reading on microturbines

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url: http://www.epa.gov/cmop/docs/microturbine.pdf (2009-12-04)
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8 Fuel cells

8.1 Technology

A fuel cell is an electrochemical cell that produces power through a reaction, triggered in the presence of an electrolyte, between the fuel (on the anode side) and an oxidant (on the cathode side). The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Currently a couple of fuel cells are available, which can be allocated to different fuel cell families as shown in the table below.

Tab. 8-1: Family of Fuel Cell Technologies [18]

Type	Efficiency	Operating Temperature
Solid Oxide	45-65%	800°C
Molten Carbonate	50%	650°C
Phosphoric Acid	40%	200°C
Alkaline	50-60%	80°C
Direct Methanol	40%	80°C
Polymer (PEM)	40%	50°C

A modular design allows for custom power generation and generation close to the load, reducing transmission and distribution losses. Fuel cells are expected to generate power with higher efficiencies (between 40-60%) than turbines. The thermal output for heating can be used and the potential efficiency can rise over 80 percent (cogeneration). Some systems are air-cooled, so water is not needed.

Methane driven fuel cells can work with gases in a concentration range between 30 – 100%. Generally CMM powered fuel cells could have some advantages in operation. They can use methane from mine pre-drainage and medium quality gob gas. Also methane diluted with air and/or carbon dioxide can be utilised. The exhaust gas should contain less NO_X and SO_2 compared to internal combustion engines. Following more information on SOFC and MCFC fuel cells as potentially interesting types for CMM utilization is given.

8.1.1 SOFC Fuel Cell

In a solid oxide fuel cell (SOFC) design, the anode and cathode are separated by an electrolyte that is conductive to oxygen ions but non-conductive to electrons. The electrolyte is typically made from zirconium doped with yttrium.

In general, on the cathode side, oxygen catalytically reacts with a supply of electrons to become oxygen ions, which diffuse through the electrolyte to the anode side. On the anode side, the oxygen ions react with hydrogen to form water and free electrons. A load connected externally between the anode and cathode completes the electrical circuit.

The real SOFC can be fed by other fuels than hydrogen (even without hydrogen at all). The general working principle of SOFC is passing oxygen ions through the electrolyte by the oxygen pressure difference between cathode and anode sides. An example of a SOFC with its components is shown in Fig. 8-1.

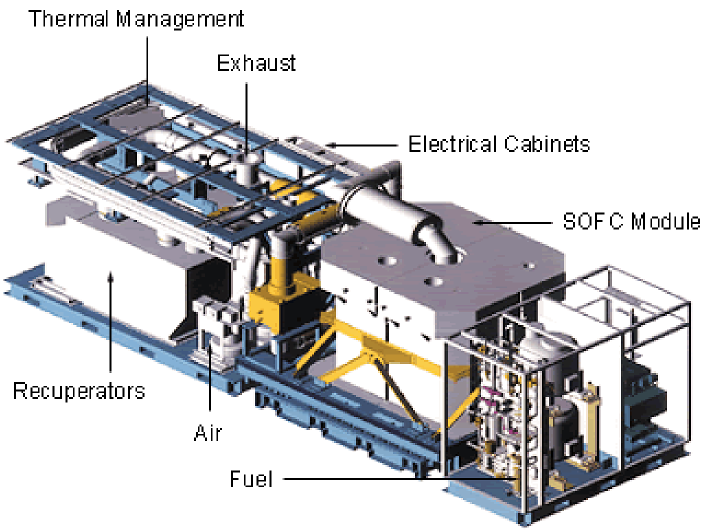

Fig. 8-1 : Major Components of a 100 kW SOFC Currently Operating in Hannover, formerly in Essen, Germany (Diagram courtesy of Siemens Westinghouse Power Corp.) [19]

Solid Oxide Fuel Cells (SOFC) offers the stability and reliability of all-solid-state ceramic constructions. High-temperature operation, up to 1.000°C, allows more flexibility in the choice of fuels and can produce very good performance in combined-cycle applications. SOFCs approach 60 percent electrical efficiency in the simple cycle system, and 85 percent total thermal efficiency in co-generation applications.

According to EPA "at present, fuel cells are economically competitive with conventional forms of electricity generation only in certain cases. Fuel cells are, however, making steady progress toward the goal of widespread commercial use. Use of methane in fuel cells, recovered from gassy coal mines, may be an economical approach to on-site power generation or local use.

Gob areas (collapsed rock over mined-out areas) release large volumes of gas and subsequently vent it to the atmosphere. Much of this gas is medium-quality and unsuitable for pipeline injection. However, fuel cells can operate on medium-quality gas, reducing methane emissions to the atmosphere while producing electrical power for on-site use. Because of their high efficiency, the use of fuel cells for power generation emits less carbon dioxide per kilowatt-hour of electricity produced than conventional turbine and internal combustion power generation methods. Solid oxide fuel cell (SOFC) power systems have already demonstrated extremely low emissions (less than 0.5 ppm NOx, no SOx, CO or unburned hydrocarbons), making permitting easier and less expensive.

Solid Oxide Fuel Cells (SOFCs) are currently being demonstrated in sizes from 1kW up to 250-kW plants, with plans to reach the multi-MW range. A 200 kW SOFC sited at AEP Ohio Coal LLC's Rose Valley Mine Site in Hopedale, Ohio can be given as an example of use (Fig. 8-2). SOFCs utilize a non-porous metal oxide electrolyte material. SOFCs operate between 650 and 1000°C, where ionic conduction is accomplished by using oxygen ions." [19]

Fig. 8-2: 200 kW solid oxide fuel cell (SOFC) sited at AEP Ohio Coal LLC's Rose Valley Mine Site in Hopedale, Ohio. (Photo courtesy of FuelCell Energy Inc.)

8.1.2 MCFC Fuel Cell

Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. Because they are more resistant to impurities than other fuel cell types, scientists believe that they could even be capable of internal reforming of coal, assuming they can be made resistant to impurities such as sulphur and particulates that result from converting coal, a dirtier fossil fuel source than many others, into hydrogen.

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, are decreasing cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs that increase cell life without decreasing performance.

MCFCs are medium high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminium oxide ($LiAlO_2$) matrix. Because they operate at extremely high temperatures of 500°C to 650°C (roughly 1,200°F) and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs.

Molten carbonate fuel cells can reach efficiencies approaching 60%, considerably higher than the 37%–42% efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85%. Molten carbonate fuel cells are not prone to carbon monoxide or carbon dioxide "poisoning" — they can even use carbon dioxides as fuel—making them more attractive for fuelling with gases made from coal. In a MCFC methane is used as fuel. It has to be reformed, which can be done in the Indirect Internal Reformer (IIR). The IIR is a flat reactor located between the single cells of the fuel cell stack. Within this reactor the methane reforming as well as the water gas shift reaction take place. The reaction products CO and H_2 are used as fuel in the electrochemical reactions. Further on, the temperature distribution of the fuel cell stack is influenced by the endothermic reactions within the IIR. The temperature in turn is one of the important values to describe the state of the fuel cell stack. The reaction rates (efficiency) as well as the material degradation (life time) depend on the temperature. Therefore a model of the IIR is an important tool for the optimization of the temperature distribution within the fuel cell stack.

8.2 Examples of use

Moonlight Project:R&D in Japan is mainly conducted under the Moonlight project. The target of this project is the development of a 1kW external reforming MCFC pilot plant.

8.3 Further reading on fuel cells

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9 Utilisation overview

The technology chosen for a project depends on the CMM quality and on the other hand on the possibility for sale or use of products. The next point of view could be the robustness and the status of development of the technology, which would be suitable for the given project site.

Proved and tested technologies for the methane concentration more than 25% in the CMM are listed in Tab. 9-1. The only proven technology for power production from CMM is the burning in gas engines with or without heat production. Boilers are a suitable solution for the heat production, if there is no possibility for power use or for power grid access. The last technology – LNG production - makes a methane use in a distance from the project site possible. The product, liquefied methane, can be used as fuel for special equipped vehicles or boilers and burners.

Tab. 9-1 Proved and tested technologies

	Technology	CH_4 [%]	Status	Products	Remarks
1	Engines	(25) 30 - 100	proved and tested	§ Power § +/- heat § Emission reduction	Since 1996 over 100 units are in operation
2a	Boiler monovalent Burners	(20) 25 - 100	proved and tested	§ Heat § Emission reduction	Since 1980 th
2b	Boiler additional fuel Burners	(20) 25 - 100	proved and tested	§ Heat § Emission reduction	Since 1900 on mines
3	CMM flaring	20 - 100	proved	§ Emission reduction	Used on landfills
4	LNG	50 - 100	tested	§ LNG § Emission reduction	660 mio. m^3 in 2006 US

Some new technologies listed in the table below are on different stages of development. The special attention has the VAM utilisation, already implemented at some mines, as a technology for the use of very low concentrated CMM. Due to its very high investment costs and technical requirements it is unlikely, that this technology will be frequently implemented in the next years.

Tab. 9-2 Technologies that has to be developed further

	Technology	CH_4 [%]	Status	Remarks
5	VAM Utilization	0,2 – 1,2	demonstration	Some are in operation
6	Gas Turbines/ Micro turbines	40 - 100	demonstration	
7	Fuel cells	30 - 100	Pilot	

As the local conditions, methane concentration, pressure, dust, stable quality and quantity, are different at each project site, the robustness of a technology is crucial for the project development. The Tab. 9-3 gives an overview on the sensitivity of the proven and tested technologies against the quality changes.

Flaring and co-fired boilers has for example very low expectation on the stability of CMM quality. The high defined gas engines require stable gas quality for a sufficient operation. An utilisation of CMM beside thermal conversion is very seldom due to uncertainty of long term CMM supply for big amounts of gas and at the same time very high requirements on the gas quality.

Tab. 9-3 Robustness of operation of the utilisation technologies

	Technology	CH_4 [%]	Robustness against changes of			
			Concentration	Pressure	Moisture	Dust
1	CMM flaring	(20) 25 - 100	++	++	++	+
2a	Boiler additional fuel Burners	(20) 25 -100	++	+	++	+
2b	Boiler monovalent Burners	(20) 25 -100	+	○	+	+
3	Engines	(25) 30 - 100	○	-	-	-
4	LNG	50 - 100	-	++ *	++*	++*

++ very good + good ○ moderate – bad -- very bad

* special gas treatment and compression necessary

In fact the local conditions have the highest impact of the chosen technology. Especially on active mines the quality of the degassing process is important for a high degree of utilisation. The methane use has not the highest priority for the operation of degassing system, which is mainly installed due to ensure the safety of the mine, but sensitive utilisation plants excuses only slow quality changes. High operational costs, short life time of the equipment and interrupts in the production are results and at the same time a very high risk of CMM projects.

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