Analysis on evaluating the concentration of ventilated air methane in the coal mines using a thermodynamic approach

Ventilated air methane is usually released from the mine ventilation shafts in the coal mines. It contributes in a considerable extent on the increasing of the greenhouse gas emission in the atmosphere. The mitigating approach of this methane emission to the atmosphere is dependent on the controlling and monitoring the emission of this gas. That is why the concentration of the methane gas in the ventilated air and its oxidation mechanism to convert into another carbon molecule must be evaluated. In this study, there had been tried to propose an approach by which the thermodynamic oxidation mechanism is integrated with a hot power cycle to evaluate the required energy variation and efficiency variation according the variation of methane concentration and volume. This was the main purpose of this proposed study. Not only that, but also the mass and energy applied here are balanced and after that, it is easier to get a concept about the amount of cost to utilize the ventilated air methane per unit of methane.

Keywords: Ventilation air methane; thermodynamic efficiency; oxidation process, decarbonization process; compression ratio.

1.0 Introduction

Methane and carbon dioxide are the most potential contents of greenhouse gas. Though, carbon dioxide gas has various prominent sources to release into the atmosphere, but methane has not so many. Methane is released mostly from the coal mining activities specially from the mine ventilation shafts [1]. During the underground coal extraction, methane that is stored between the coal layers both in adsorbed and absorbed states releases into the ventilated air after mixing with the airflow in well manner. Though, the concentration of methane in the ventilated air is low to consider, still this low content can bring a bigger problem, when it tries to convert into the carbon monoxide or carbon dioxide gas in the atmosphere. The ventilated air from the coal mining activities contributes approximately 8-10% of methane in worldwide to greenhouse gas. This ventilated air methane (VAM) fluctuates the condition of mine working faces, if it is not controlled and monitored properly [2]. There is always a possibility of occurring a mining hazard in the working area. That is why it has become very important to mitigate the effects of air methane on the working situation [3,4]. But, before mitigating and controlling the flow of methane gas, it is compulsory to evaluate the concentration of methane in the ventilated air and determine the criteria for which the concentration of methane can be influenced by the system efficiency and supplied energy from outward energy source. The efficient utilization and conversion of ventilated air methane for an economic purpose has been initiated from a decarbonization coal power plant [5]. In this plant, the energy supplied from turbine converts methane into flue gas to initiate an air hot power cycle for an efficient oxidation process [6]. After that, the mass and energy are balanced for this suggested system. Finally, the observed results are evaluated to provide a concept about the thermodynamic activities of VAM. Here, for building up a simple concept about the conversion of the ventilated air methane into further simple carbon products, an overall mechanism has been shown down in below step by step as:

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

$$CH_4 + (3/2)\ O_2 = CO + 2H_2O$$

These reactions can be further processed as:

$$CH_4 + H_2O = CO + 3H_2$$

$$2H_2 + O_2 = 2H_2O$$

$$CO + H_2O = CO_2 + H_2$$

By following the above mentioned reactions, the oxidation of ventilated air methane can be controlled for using as a primary or secondary fuel in newly developed approach which is unfortunately not the purpose in this study.

2.0 Methane emission in the atmosphere from coal mining activities

Coalfields are mostly accounted for the higher emissions of methane in the atmosphere. Coalfield is the fourth largest source for releasing methane gas than the potential sources like, burning of natural gas, fertilizer production, landfills etc [7]. It is estimated that coal mines are responsible for the 15 per cent emission of methane all over the world. Methane

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gas can be emitted in the atmosphere generally in four coal mining activities:

- Surface mining activities,
- Underground mining activities,
- Post mining activities,
- Mining at abandoned spaces.

According to a report of IPCC about global warming assessment, it was stated that the effect on the global temperature by methane gas is 72 times higher than that by the carbon dioxide or carbon monoxide gas. This effect on the climate changing is increased again more when the methane gas is oxidized more to form carbon dioxide gas in the atmosphere. It is predicted that, the concentration of the quantity of methane gas will be doubled in the atmosphere by the year of 2040. A study is found from a report done by National Renewable Energy Laboratory acquainted that underground coal mining releases 4.2 grams of methane per kilogram of coal, where the surface coal mining releases about 1.2 grams of methane per kilogram of coal. A general estimation of the methane emission for coal mining by the year 2015 is described in Table 1. Also, an overview of the methane emission from the coal mining activities from the year 1980-2020 is indicated in Fig.1.

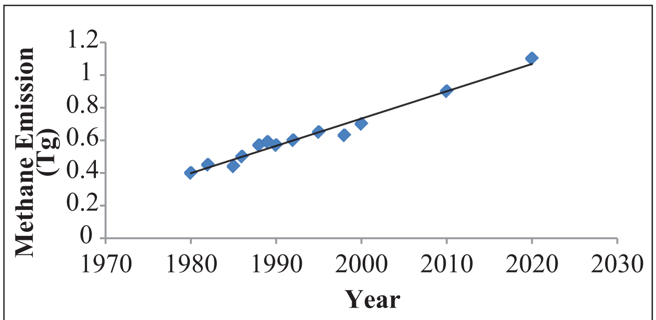

Fig.1: Overview of the methane emission from the coal mining activities by the 1980-2020

Table 1: Methane emission in the atmosphere from different types of coal mining activities by the year 2015

Type of mines	Coal production (million-ton)	Emissions factors (m^3/t)	Methane emission (Tg)
Underground Mining	55.31	2.93	0.12
	13.83	13.06	0.13
	0.87	23.65	0.01
Post Mining (Underground)	55.31	0.99	0.04
	13.83	2.16	0.02
	0.86	3.11	0.00
Surface Mining	531.85	1.18	0.42
Post Mining (Surface)	531.85	0.15	0.05
Total emission (Tg)			0.79

Note: Data are compiled from an open source.

The content of the methane gas can be determined even in the low amount by the Gas Chromatography using with a flame ionization indicator. This instrument detects mainly the amount of carbon ions produced for combustion of carbon products. The amount of ions is directly proportional to the amount of carbon products in a sample. Though, the flame ionization detector cannot be affected by the noncombustible products. Still, it is familiarized as a destructor for its power of pyrolization, where two electrodes are applied to measure the currents to produce carbon ions.

3.0 VAM quantification study

To initiate the study of quantifying the concentration of ventilated air methane, the first step would select the appropriate locations of the inlet and outlet entries of the mine plants. Then, the all types of behaviours of the ventilated air methane can be properly monitored. The routes of intake and exhaust air in the coal mines are needed to be developed with advanced infrastructure so that the surveying on the methane emissions in the coal mines should not face any inside or outside problems. This quantification study measures the concentration of methane in the air flow in every working faces or stations using this surveying [8,9]. The elemental content of mixed molecules in the emitted air flow is evaluated at each working face. For this study, a rigorous and detailed technique needs to be applied to measure the methane emission. The sample should be taken from the main intake and return pathways of emitted airflow. A full working day is taken as a study period for this job to count the elemental data of the VAM subsequently. Then, these periodic emission rates are added to find out annual rate of a coal mine. A schematic change of VAM concentration during a producing day is shown in Fig.2. Finally, the observed data would be correlated with the coal production data to evaluate the quality of the coal methane production along with the coal rank (Table 2).

Table 2: An estimation of VAM at coal mine

Details	Current production level	Increased production level (at coal production 2100 ton per day)
Air flow quantity	12000 m^3/min	12000 m^3/min
Air discharged (per day)	17.28 Mm^3	17.28 Mm^3
Air discharged (per year)	6.3 Tm^3	6.3 Tm^3
Emitted VAM in percentage (V/V)	12.6 Mm^3/yr	31.6 Mm^3/yr
Mean VAM estimate	9.4 Mm^3/yr	18.9 Mm^3/yr
CH_4 discharged	6.024 t/yr	12.049 t/yr
Equivalent reduction of CO_2 emission	10.9947 t/yr	219.893 t/yr
Earned carbon credit @ $10/tonne	1.10 M$/yr	2.20 M$/yr

Note: Data are compiled from open source.

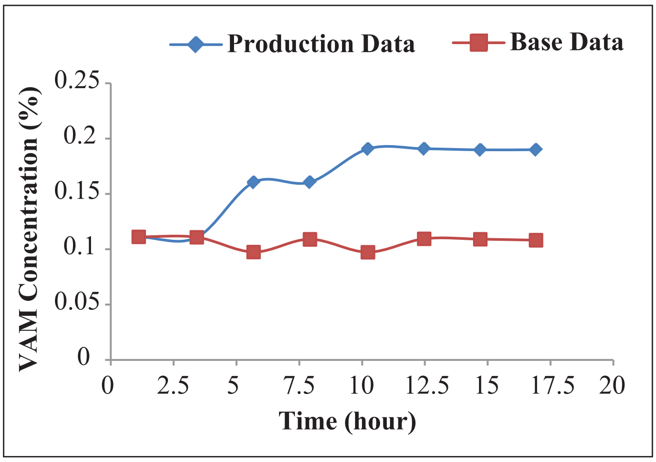

Fig.2: Schematic change of VAM concentration during a producing day

4.0 Thermodynamic approach of evaluating the integrated system of ventillated air metahne

This concept is made with a hybrid energy/power production system of coal and VAM. This system gives a view that the electricity and power for the coal and VAM closely have equal value for their integrated substantial energies [10,11]. The total calculated energy efficiency is used as a basic criterion to evaluate thermodynamic efficiency of the system which is designed as below:

$$\varepsilon_{net} = \frac{P}{Q_{in}} = \frac{P_{VAM} + P_{coal} - \sum P_i}{m_{coal} \times LHV_{coal} + m_{VAM} \times LHV_{VAM}} \quad \text{... (1)}$$

Where,

P = output electric power of the system (MW),

Q_{in} = input electric energy of the system (MW),

P_{VAM} = output electric power (MW) only from the VAM-power production system,

P_{coal} = output electric power (MW) from oxy-combusted coal plant,

$\sum P_i$ = cumulative auxiliary power consumption (MW),

LHV = lower heating value (MJ/kg),

m = mass flow rate (kg/s).

Moreover, the degree of effects on the saving of fuel is estimated from the energy and power reclamation of the system can be presented by a term 'Energy Saving Ratio' by the following way:

$$ESR = \frac{\Delta Q_{in}}{Q_{in-ref}} = \frac{\left(P_i/\varepsilon_{net-i} + P_{ii}/\varepsilon_{net-ii}\right) - \left(P_p/\varepsilon_{net-p}\right)}{P_i/\varepsilon_{net-i} + P_{ii}/\varepsilon_{net-ii}} \quad \text{...(2)}$$

Where,

ΔQ_{in} = least input energy (MW) of the proposed system compared to the two reference systems with the equal output power,

$Q_{in\text{-}ref}$ = input energy of the reference systems,

P = proposed systems,

i, ii = reference systems.

5.0 Economic evaluation of the thermodynamic approach

To count the economic feasibility of this thermodynamic approach of the mitigation of VAM, the priorities should be given on per unit of cost of electricity for the proposed system based on the references. So,

$$COE = \frac{FC_L + CC_L + OMC_L}{P \times N \times w} \quad \text{... (3)}$$

Where,

FC_L = annual fuel cost (\$/year),

CC_L = annual carrying charges (\$/year),

OMC_L = annual operating and maintenance cost,

N = number of operational hours of the plant per year (h/year),

w = factor related with average capacity.

To measure the annual fuel cost, the wasting materials should be discharged as a low energy density material through the ventilation system. However, no additional device may not be adopted to use. So, FCL is determined by:

$$FC_L = 3.6 \times m_{coal} \times LHV \times N \times w \times p_{coal} \quad \text{... (4)}$$

Where,

P_{coal} = coal price on LHV (\$/MJ).

Again, the annual carrying charge (CCL) is estimated following by the equation (5).

$$CC_L = CRF \times FCI\ (1+ \alpha) \quad \text{... (5)}$$

Where,

FCI = fixed capital investment (M\$),

CRF = capital recovery factor based on the discounted rate (K) and life of equipment (n),

α = compound interest during construction.

Capital recovery factor can be further calculated by the following form:

$CRF = [K(1 + K)^n] / [(1 + K)^n - 1$

Hereby, the fixed capital investment is determined based on the engineering equipment purchasing cost and their installation cost, some casual cost etc. For a definite suggested system, the overall quantity of fixed capital investment can be acquired by the following:

$FCI_{(overall)} = FCI_{(unit\text{-}i)} + \ldots\ldots\ldots\ldots\ldots\ldots + FCI_{(unit\text{-}iv)}$

For a fix proposed reference system i, the overall amount of fix capital investment is the summation of fix capital investment of steam turbines unit, boiler unit and compression unit.

$FCI_{(overall)} = FCI_{(turbine)} + FCI_{(boiler)} + FCI_{(com.)}$

Again, a scaling up method is used for calculating FCI as:

$$FCI = FCI_o \times (\frac{S}{S_o})^f \quad \dots (6)$$

Where,

FCI_o = fixed capital investment for a component at size S_o,

FCI = fixed capital investment for a component at size S,

F = scaling factor.

6.0 Methane concentration in VAM

The concentration of the methane in the ventilated air is measured to evaluate the value of caloric content in the ventilated air methane and the required energy for the oxidation ventilated air methane. After observing the concentration of methane, the energy distribution for the thermodynamic performance in the hot ventilated air is interpreted. Not only that, the efficiency of this thermodynamic approach related to catalytic flow in the reactor can also be evaluated. This fact can be assumed that the concentration of methane in the hot ventilated always changes due to the continuous changing of coal mining activities. With this changing of concentration of methane, the energy distribution required for the catalytic oxidizing reaction of utilizing the methane is also changing. The heat and energy supplied from the boiler and turbine for oxidation process should be maintained in a consecutive manner. The influences of the concentration of methane on the energy distribution and efficiency of the VAM oxidation are discussed in Figs. 3 and 4 respectively. Fig.3 shows the influence of methane in volume (%) on the input energy required in the coal and VAM based on the LHV analysis. And the Fig.4 shows the influence of methane in volume (%) on the efficiency of the energy. In both figures, it is found that the overall input energy associated with energy efficiency is increased in a well manner. Because, in a constant compression ratio, the enthalpies of both at outlet and inlet entries of hot air in the air turbine are enhanced. The increasing variation of input energy and energy efficiency are observed approximately by 8.3MW and 1.2% respectively, at the increasing variation of the volume of methane by 0.25-0.3%.

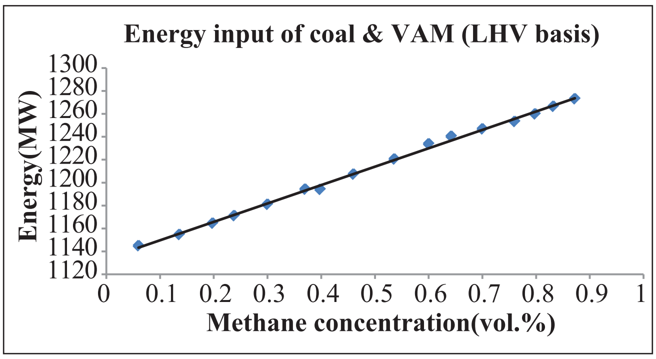

Fig.3: Influence of the methane concentration on the input energy of the system

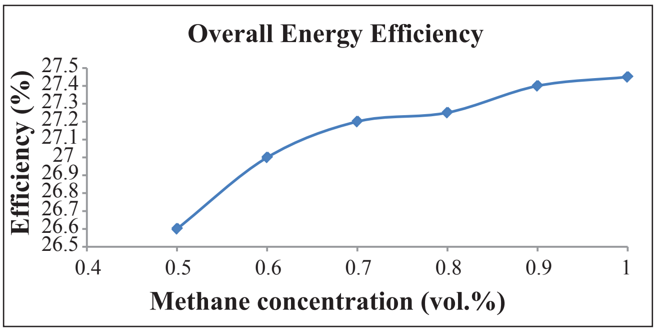

Fig.4: Influence of methane concentration on the energy efficiency of the system

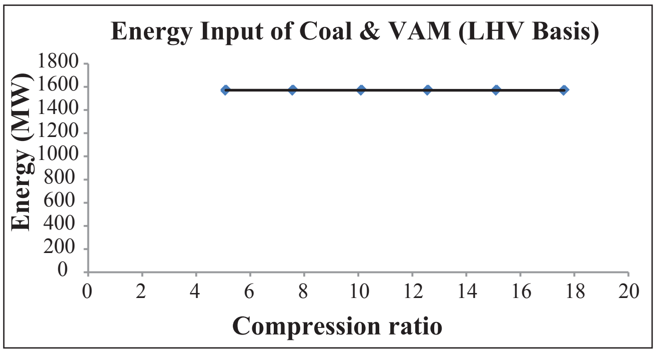

Fig.5: Influence of the compressed VAM pressure on the input energy of the system

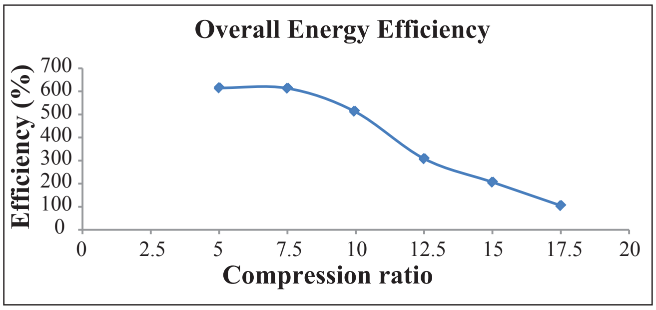

Fig.6: Influence of the compressed VAM pressure on the energy efficiency of the system

7.0 Compression ration of VAM

This time, the concentration of methane in the ventilated air is assumed constant for evaluating the influence of VAM compression on the supplied energy in hot air power cycle. The ratio of compression related to the VAM can affect the overall performance of the system. Here, the influences of VAM compression on the input energy distribution and energy efficiency of the system are displayed in Figs. 5 and 6. It can be seen from the Fig.5 that the variation of input energy distribution according to the variation of compression ratio is totally stabilized. But, on the contrary, the value of energy efficiency according to the variation of compression ratio continuously drops (Fig.6). The more the ratio of compression increases, the more the net output electric power subsequently decreases. The reason behind this fact is the requirement of the output electric power for the increasing overweighs of the output work in the turbine and boiler. The temperature of the catalytic flow reactor is kept constant. Here, the increased variation of input energy and decreased variation of energy efficiency by 5.26MW and 0.25-0.3% are observed respectively at the increased variation of compression ratio.

8.0 Economical analysis

The feasible implementations of mine site activities to assess the emission of methane are done based on the thermal efficiency and energy distribution of a VAM technology. The criteria essential for evaluating the feasibility studies of thermal approach to determine the methane concentration in the ventilated air are:

(i) Percentage volume of emitted methane in the ventilated air.
(ii) Variation of methane concentration in the ventilated air on the working station basis.
(iii) Variation of air flow rate.

To assess the economic potentiality of the qualification study of VAM utilization is explained by McPherson [12]. The variability of this utilization approach is depended on the gas flow rate per tonne of coal produced. Not only that, but also depends on the process by which the captured methane flow can be utilized to produce primary or secondary fuel. The required investment on this approach is determined mainly focus on the way of balancing the production of CO_2 from the ventilated air methane. The coal rank can also affect on the economic analysis of the thermal approach of the evaluating the utilization of VAM. A short scenario of the economical analysis of VAM is given in Table 3.

TABLE 3: ECONOMICAL ANALYSIS OF VAM.

Parameters	Rate/Production
Ventillated air consumption	4000m^3/min
Methane concentration (VAM)	0.32% CH_4
Use of VAM/minute	12m^3 CH_4
Net CO_2 reduction	91226t/yr
Rate of certified emission reduction	$7.00
Generated revenue	$645762

9.0 Conclusion

Approximately 70% of the methane is released from the coal mines during the mining activities. The methane is extremely a hazardous gas that can be resulted in flaming during the coal production time in the working area. But, the development of the utilization of emitted methane in the ventilated air subsequently reduces this orthodox concept. Now, the current state of art offers some approach to reuse the VAM as a primary or secondary fuel [13]. As methane in the ventilated air is mitigated as a form of CO_2 gas, then the reaction of oxidation in this case plays a great rule. The oxidation reaction can contribute in the field of converting 7-10% of anthropogenic methane into CO_2 gas from associated coal mining activities. The main target of this study is to reveal the power generation process involving with VAM in oxy-coal power plant. And this effort comes to the success. Finally, it is included that the efficiency of the total system is rounded at 27.2% according to light variation of input energy. The cost of required electric power is estimated by $120/MWh included with the reduction of CO_2 by 17.44Kg/MWh. The proposed theory has also been provided to design an economic technical of thermodynamic approach to effectively utilize the ventilated air methane based on the oxy-coal power efficiency.

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