Development of an automated coal mine methane extraction system

Lovejoy Gushungo
Department of Industrial and Manufacturing Engineering,
Harare Institute of Technology, Harare, Zimbabwe.

Portia Mupfumira
Department of Industrial and Manufacturing Engineering,
Harare Institute of Technology, Harare, Zimbabwe

Daramy Vandi Von Kallon
Department of Mechanical and Industrial Engineering Technology,
University of Johannesburg, Johannesburg, South Africa
dkallon@uj.ac.za

Abstract

The purpose of this project was to develop an automated coal mine methane control system for methane gas extraction from active and abandoned coal mine roofs, the lightest gas in coal mines. Zimbabwe has the richest deposits of methane gas in coal beds in Southern Africa, which accumulates into the underground coal mines during mining operations and abandoned underground coal mines. Almost 50% of the energy expended in coal mines goes to the ventilation system to ventilate the accumulated explosive gas which is also a source of clean energy. Due to the lack of cost-effective technology to capture and fully harness this coal mine methane gas, its accumulations are resulting in 10+% downtime which is a huge loss to coal mining companies such as Hwange Colliery in Zimbabwe. Analysis of methane gas behavior in terms of emission and accumulation was done, circuit designing, conceptual modeling, simulations, and 3D modeling. A system was developed which could capture methane gas through a suction process. A model of the system was developed and tested which could detect, monitor, and extract coal mine methane gas. This project is recommended for methane gas extraction inactive underground and abandoned underground coal mines in Zimbabwe and Sub-Saharan Africa and right page margins and justified.

Keywords
Coal mine, Methane extraction, Keyword 3, Keyword 4 and Keyword 5. (10 font)

1. Introduction
Methane is a natural gas that is formed under very high temperatures and pressures, due to the decomposition of organic matter. During the coalification process, the deeply buried organic matter is subjected to extreme conditions, and coal and methane are formed. The deeper the organic matter, the higher the coal rank which means the carbon content in coal will be increased as well as the quantity of methane formed. Zimbabwe has above 24 billion tonnes of coal reserves in the Hwange region of the country, which are currently the major source of fuel for thermal power generation plants as well as many industrial steam generation processes in the country, which is more than the rest of SADC region, Figure 1. According to Norman Mukwakwami, Zimbabwe's gas reserves in Hwange and Lupane regions have over 800 billion cubic of methane gas per square kilometer (Mukwakwami 2013).

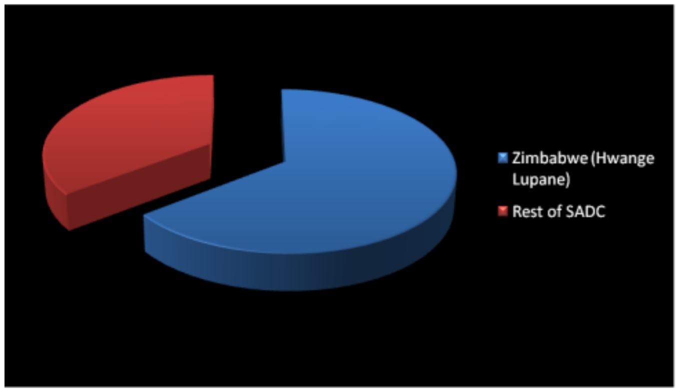

Figure 1. Comparison of Zimbabwe methane reserves and those of the rest of SADC (Mukwakwami 2013).

The accumulation and lack of suitable extracting techniques for methane during mining operations in underground coal mines have contributed to the shutting down of underground coal mines. Currently, coal mining companies such as Hwange Colliery, Sengwa, and Coal Zimbabwe are practicing surface mining operations which has a low rank of carbon content. Hwange colliery has shut down its underground coal mine as a preventive measure to the reoccurrence of the Kandunduma incident. The capture of methane gas being emitted into the underground coal mines can result in many benefits and contributions to the energy sector.

Methane is a high source of clean energy which can be used in electric power generation, co-firing of boilers, and fueling combustion engines. There are also advantages aligned with the capture of methane thus improvement of safety in mines as methane gas is highly explosive at concentrations from 2%. Furthermore, there is the possibility of achieving a reduction in greenhouse effects as it has 21 times less environmental impact relative to carbon dioxide (Talkington, 2015) and increased productivity due to reduced downtime being caused by its accumulation during coal mine operations.

The energy deficit problems currently being faced by Zimbabwe, the supply is 1400MW whilst the demand is 2400MW which calls for an alternative energy source to cub the power importation costs from South Africa, Mozambique, and Zambia (Mzezewa and Murowe 2017). Lack of methane gas extraction techniques in existing Zimbabwean underground coal mines such as Hwange hence limited utilization of richly abundant, explosive gas in the coal mining environment. This research aims to design a methane gas extraction system from underground coal mines, to aid energy availability in Zimbabwe.

2. Literature Review

The underground mining operation is the extraction of ore below the earth's surface and the major priorities are to ensure a safe environment both for people and equipment. The designing and supporting structures enhance the safety of the mine. The standards of the mining operations are dependent on the resources which are being mined for example in coal mines more attention is given to the ventilation of methane gas. The accumulation of methane gas in underground coal mines will result in the explosion or asphyxiation of personnel (Tshitema et al. 2020). Methane gas extraction technologies have been continually improved over the past decades to capture most of the methane formed during the coalification process while maintaining a safe environment. Coal bed methane extraction techniques are classified according to the nature of the extraction process, there are three main techniques thus Pre-mining drainage, Coal mine methane, and post-mining methane (Mandal et al. 2013).

Methane gas monitoring is one of the major priorities in coal mines, the miners need real-time based feedback on their operating environment. Its explosive properties are a major threat to workers, its control is very crucial to maintain the statutory stipulated concentration below 2%. There have been technological advancements and developments in the design and manufacture of methane gas sensors to continually improve gas detection systems' robustness in underground mining. These environments have very high fluctuations in humidity, temperatures, and poisoning from some gases being emitted during extraction operations (Zhang et al. 2014, Xiaodong et al. 2014).

2.1 Methane gas detection systems

There are different types of controllers that can be used in the monitoring of coal mine methane gas in underground coal mines. They act as the brain which receives data and acts or executes based on a set of rules and facts and makes decisions to maintain or attain the desired conditions. Figure 2 shows a typical PLC basic operation, the sensors for example MQ4 methane gas sensors will be detecting the percentage of methane gas in the mine. The methane gas percentage is fed into the input module as a readable signal voltage or amperes, the signal is fed into the central control unit (CCU) and basic on the programmed rules the central control unit gives command inform of a signal which is transmitted to the actuators. suction pumps, alarm and extraction fans. The CCU makes the decision based on the PLC program. The alarm systems are a necessity for fixed methane detection and control systems, they should be located at more than one location and room to alert the people about the current working environment. It should be possible to see and hear the alarm indicating hazardous situations. A series of differentiated notification alarms are a need for the sake of optimum productivity because once employees feel safe, they will perform at their maximum possible efficiency, thus high production rate. The methane accumulation alarms should be audible and distinguishable from fire alarms (Health and Safety Executive. 2011).

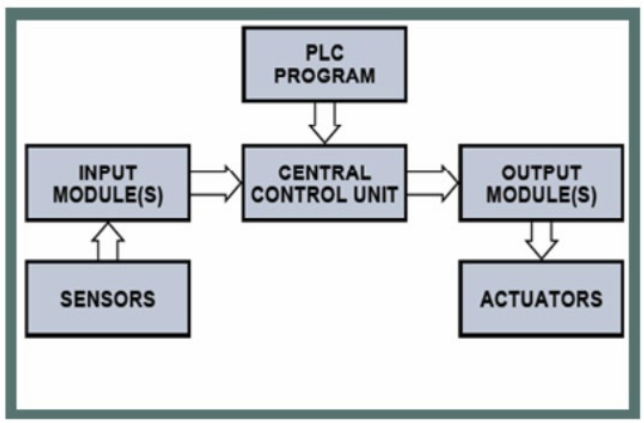

Figure 2. PLC Basic operation (Mandal et al., 2013).

Methane gas is a highly explosive gas that requires specific storage conditions, dry, cool, out of direct sunlight, and well-ventilated areas. It must be stored under pressurized conditions of up to 50 Mpa and at a supercritical temperature, above 273.15K, storage pressure vessels are used for the storage of methane gas. According to Factories and Works Regulations, RGN 303 of 1976 a pressure vessel is a container designed to hold a material below or above the atmospheric pressure. The design, fabrication, testing, inspection, and fabrication are detailed in the American Society of Mechanical Engineers (ASME) Section VIII. There are 3 main types of vessels thus storage vessels, heat exchangers, and process vessels (Chauke et al. 2019). The design and manufacture of pressure vessels are governed by ISO standards based on the type of the pressure vessel. Considering type III pressure vessels, the ISO 11439 is considered due to the safety factor of 2.53. Materials such as aluminum, carbon fiber, and carbon steel were considered, aluminum and carbon steel offered advantages such as lightweight and less expensive but considering the operating conditions and structures carbon steel was considered due to its high life span.

3. Feasibility study

Hwange Colliery Company Limited is the largest coal mining company in Zimbabwe owning more than 4200Ha (42 km^2) of coal bed methane (Mukwakwami 2013). The term coal bed methane is used to refer to coal seam or reserves that are predominated by methane gas. These sources of natural gas have not yet been exploited due to a lack of cost-effective technologies which can be implemented in their ancient designed underground coal mines. Focusing on the methane gas emissions, the Zimbabwe Peace Project raised a concern about the fire cooling methods being used to put out a fire in the open cast mines. These fires are caused by the methane emissions from the coal bed during mining operations. Shangani Energy Exploration has been extracting methane gas and its records reviewed that the methane gas being pumped out has a purity level of over 97 % (Mukwakwami 2013). The technology of the extraction system to be applied should not affect the residence of Hwange as it is located close to communal land, they practice subsistence farming and animal husbandry. The quantity surveys reviewed that the coal mine methane gas concentration is usually in the range of 25 to 60 % purity, but they are associated with high fluctuations (Talkington 2015).

This paper investigates the permeability, methane gas emissions recorded by Hwange Colliery, methane gas properties, its control and mitigation, and also how best it can be extracted without affecting mining operations but instead reducing downtime caused by its accumulation. The paper applies the following data collection techniques such as interviews, documents and records from Hwange Colliery, questionnaires and surveys. Simulations and statistical graphs estimation of the emissions of methane gas during coal mining were also incorporated as well as the mining environmental effects such as humidity dusty and temperatures. Engineering software such as Solid Works and AutoCAD was used to simulate the mechanical behavior of the selected material. The conceptual solutions developed were based on the detection of methane gas in coal mines, control, and sizing of the suction pumps, the safety stake lights, and alarms as well as the gas storage system.

4. Conceptualization and development

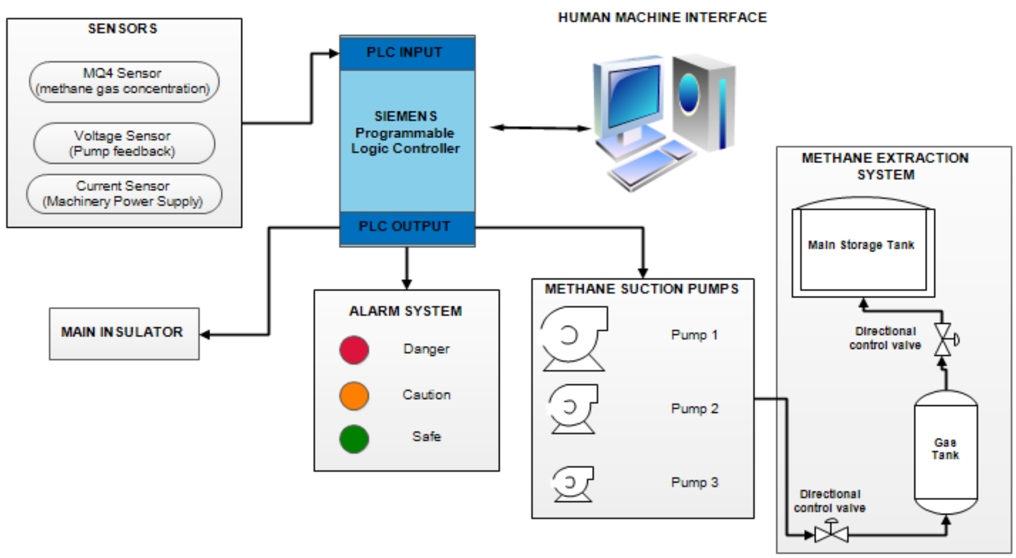

Figure 3. The developed concept.

Figure 3 shows the developed concept, which consists of sensors, MQ4 sensor for methane gas detection, a voltage sensor for suction pump feedback, and a current sensor for machinery power supply which ensures total shutdown of machines during emergence. A PLC controller which is the brain of the whole methane detection and control system consists of a programmed language with given rules and conditions to which the whole system should respond when the methane gas concentration goes above 3%, which alarm lights to activate, extraction fans to start and monitoring of the storage tanks conditions. The alarm system is an actuated output based on the methane gas level green representing safe, orange it is proceed with caution, and red danger depending on the detected methane percentages. The controller gives an actuation command to the suction pumps based on the degree of methane gas percentage detected. As you can see the pumps have different sizes, pump 3 is the smallest one it is kept running to, 0.01 to 0.5%, pump 2 - 0.5 to 1%, and finally, pump 1 the biggest is activated when methane gas percentage > 1%. The design of a methane gas extraction system for underground coal mines will not only recover the valuable source of clean energy but many benefits such as increased productivity due to reduced 10+% downtime (research done by (Talkington, 2015) caused by coal mine methane gas accumulation, improvement of mine working conditions in terms of safety and reduction of greenhouse effects. The introduction of this detection and extraction system in underground coal mines will also be a great input in terms of the mine's compliance with statutory requirements. The methane captured will contribute to the energy system in Zimbabwe, it can aid in steam generation industrial processes, tobacco curing, or even some operations at the mine which might need energy or heat. This system will give real-time-based methane gas concentrations in the mine, it will also inform the workers through alarms when the methane gas concentration has gone above the safe operating limits. There are also advantages aligned with the capture of methane thus improvement of safety in mines as methane gas is highly explosive at concentrations from 2%, reduction in greenhouse effects as it has 21 times less environmental impact relative to carbon dioxide, as well as increased productivity due

to reduced downtime being caused by its accumulation during coal mine operations. Considering the current status of the Hwange Colliery underground mines are shut down due to non-conformance of the mine statutory requirements. Based on Talkington's research on the impacts of 10% downtime due to methane gas accumulation was evaluated based on the Hwange Colliery Company's mining records.
The production rate of Hwange Colliery Underground mine is 600t/shift (8 hour shift), thus 1800 t per day.
Production rate per hour = 1800t/24Hours
= 75 t/hour
10% of 24 hours = 0.1×24 hours
= 2.4 hours
Now the loss in production per day is = 75 t/hour × 2.4 hours
= 180 t in a day
Considering Hwange loss in a month, 30 days ≈ 30 × 180 t
≈ 5400 t
Current price of coal = \$59/tonne
Amount lost in \$ = \$59/t × 5400t
= \$318 000/ per month

Hwange Colliery Company is currently focusing on surface/open cast mining which produces less quality coal bed quality rank than underground mining. Currently, no mining operations are being done in the underground due to the coal mine methane accumulations and lack of effective techniques to control and monitor the gas.
Considering the figures produced by Shangani Energy Exploration for 6 months, thus methane gas purity levels of 97% reveals that the gas reserves can be used to generate electricity for the next 200 years. The study is limited to the feasibility analysis and detection of methane extraction from available coal mines and the development of methane gas extraction and storage systems. Therefore, the use of the extracted gas by the end-user is not covered in this study.

4.1 Concept Pseudocode

The suction process starts only after the confirmation of receiving vessel, buffer storage 1 is not full.
If input 1(methane sensor) is less than 0.01%, Environment is safe and no actuation.
If input 1 is 0.01 to 0.5%, activate alarm Stage 1 (Green light), Activate Pump 3.
If input 1 is 0.5 to 1%, activate alarm Stage 2 (Orange light), keep pump 3 running and activate pump 2.
In input 1 > 1%, activate Alarm stage 3 (Red light), keep pump 1 running, pump 2 running and activate pump 1.
If input >=2%, activate Alarm stage 3 (Red light), keep pump 3 running, pump 2 running and activate pump 1 and Activate the Main supply insulator.
If input 2 (pressure sensor), reaches (90% SWP…..), notify the operator through a signal.
If input 3 (pump 1 monitor) is 1 then pump 1 is active.
If input 4 (pump 2 monitor) is 1 then pump 2 is active.
If input 5 (pump 1 monitor) is 1 then pump 3 is active

4.2 Pump feedback

When the data from the MQ4 sensor has been fed into the controller (PLC), the controller will process the data through a set of instructions in the program, rules, and facts to come up with the desired decision to keep the working area safe and to extract the methane gas present. This is more of closed-loop feedback that monitors the system. There is a linear

relationship between electric motor speed, rpm, and a tachometer output voltage. In this study, the tachometer technology is programmed in such a way to produce a digital output voltage whereby:
i. A 0V represents an inactive suction pump,
ii. A 5V output represents the motor at its maximum possible speed.
From this, the pressure sensor reading can be taken according to Johnson (Kissel 2006), thus:

Pressure, P=C_c/V_ex × 〖CV〗 _meas/CF (1)

Where:
C_ts is Full-Scale capacity –maximum pressure which the transducer should receive,
V_ex is Excitation Voltage-the recommended input voltage,
CV_meas is the Measured Voltage –raw voltage returned by the sensor,
CF is the Calibration Factor- the output of the transducer usually expressed in mV per V input.
For the system buffer storage vessels will have a capacity of 2.206MPa
With a calibration factor of 0.5v/V
The output range Voltage is 0 - 5 V
320psi = 5 volts
1psi = 5Volts/320psi
=0.016Volts
= 16mV

For every 1psi an output signal of 16mV will be produced.
The Calibration Factor is 16mV:
For the Coal mine, the methane gas reserve tank will store gas at 20Mpa which is approximate.
The capacitance output range is 0 – 5V.
Thus 2900psi = 5V,
For every 1psi an output voltage signal is 2mV/psi,
The Calibration Factor is 2Mv

4.3 Control and monitoring system

Where :x is methane gas concentration,
S1=pressure feedback of receiving vessel,
RV1=receiving vessel relief valve,
P1 = suction pump 1,
P2= suction pump 2,
P3= suction pump 3,
MV1= Motorised control valve 1,
MV2= Motorised control valve 2.

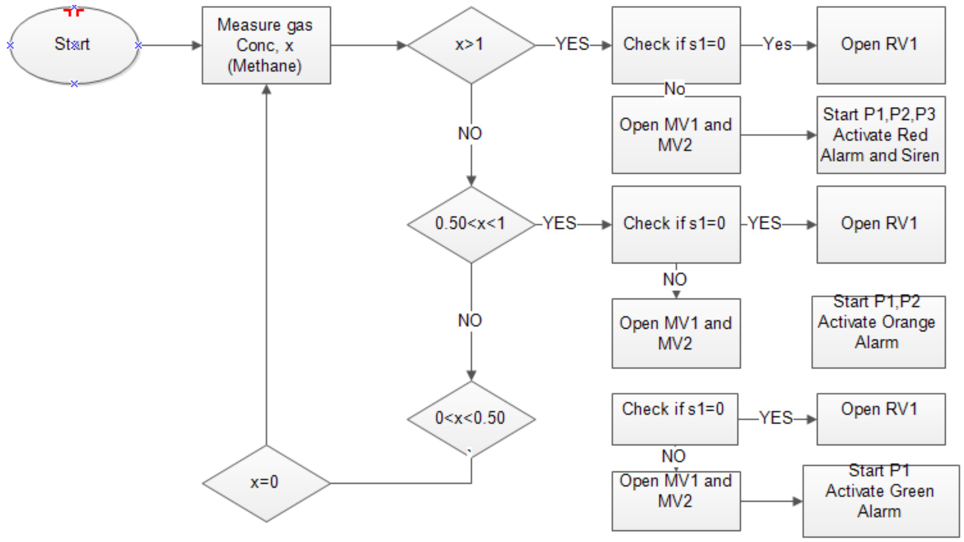

Figure 4. Control Algorithm development.

The American Society of Mechanical Engineers standards (ASME) are applied in the vessel design, Section 3 Division 1 of Dot 3AA for Compressed Natural Gas Vessels (CNG). The vessel material selection is based on the functionality requirements and the conditions in which the vessel is supposed to operate in. After all, the constraints are loaded including the atmospheric conditions, pressure, and temperatures of the locations thus a maximum of 60 degrees Celcius and 1 atm. They were considered as the external conditions during simulation. The American Society of Mechanical Engineers satisfied two types of carbon steel of materials for storage of compressed natural gases thus A516 Grade 70 and ASME SA516 Grade 70.

5. Recommendations

The underground coal mining operations can resume if this system is adopted this can result in the extraction of high-quality coal and a high source of clean energy (methane gas). Hwange Colliery currently is fully engaged in surface coal mining operations only. Shangani Energy Exploration has been extracting methane gas and its records reviewed that the methane gas being pumped out has a purity level of over 97 %. Underground coal mines will create more employment opportunities for Zimbabweans as well as aid the shortage in electricity/energy supply (supply is 1400MW whilst the demand is 2400MW). The emission of coal mine methane is not constant it fluctuates and this system can still operate at low costs due to the design of three different sized pumps for gas suction purposes. The impacts of the projected 10% downtime from Talkington's research to Hwange Colliery operations can also be minimized.

The coal mine extraction system can be improved in many various ways for effective gas capture and efficiency in providing real-time-based data of mine gas concentrations:

i. Enhanced sensitivity methane gas sensors, specifically standalone sensors which cannot be affected by mine operations disturbances.
ii. Retrieval of coal mine goaf gas? emitted gasses on the coal mine flow.
iii. More advanced methane gas purification processes are cost-effective.
iv. A SCADA system monitors all the commands before being executed and can cover the whole mining operations.
v. An adjustable ventilation system that can concentrate on high percentages of accumulated mining areas.
vi. Introduction of low methane gas percentages based steam engines which can utilize captured ventilation methane gas at Hwange Colliery.

6. Conclusion

The developed concept which can detect, control and extract methane from underground coal mines can be successfully applied in Hwange. The high methane gas emissions being recorded by Shangani Energy Exploration can make a difference in the power supply and mining of underground high-quality coal. The PLC is robust in mining environment conditions such as high temperature, dusty and humid which ensures efficient operation and control of the methane gas. The detection system, MQ4 sensor will ensure the safety of the coal miners with the help of the alarm signals which provide real-time based mine conditions. The system also has a switch to the machinery power supply which shuts down all the equipment during emergencies.

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