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Challenges in undertaking inertisation of fires in underground mines

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ABSTRACT: Inertisation is used to enhance the safety of underground mine areas either to avoid the potential for a combustion event or to stabilize a situation after an ignition, fire or heating. The primary objective of a recently completed Australian Coal Association Research Program (ACARP) study was to review coal mine inertisation and in particular to focus on use of the Polish mine fire simulation software Ventgraph to gain better understanding of how various inertisation units interact with the complex ventilation behavior underground during a substantial fire. Critical aspects targeted for examination under the project grant included location of the unit for high priority fire positions, size of borehole or pipe range required, time required for inertisation output to interact with and extinguish a fire, effects of seam gases on fire behavior with inertisation present and main fan management. A major accomplishment of the project has been to take findings from the simulation exercises to develop inertisation related modifications to the Ventgraph fire simulation program in conjunction with the Polish program authors. Selected mines were "evaluated or audited"as to the ability to deliver inert gases generated from GAG units to high priority underground fire locations .A coding system has been developed and many potential underground mine fire sources cannot be successfully inertized with the GAG docked at the current specified point; this is particularly so for fires in extended areas of workings or in panels. There is a limit to the ability of the GAG jet engine to deliver exhaust down smaller dimension borehole. There is a need to examine the use of the GAG for production or proactive uses in a wider application in Australian mines responding to recovering from mine fires, spontaneous combustion heating's, elimination of the potential explosibility of newly sealed gobs or inert mines or mine sections on closure. Some of the current uses of low flow inertisation facilities could be more effectively undertaken with the GAG unit.

1 Introduction

The primary objective of the study was to use mine fire simulation software to gain better understanding of how inertisation (GAG, Mineshield, Pressure Swing Adsorption and Tomlinson Boiler) units can interact with the complex ventilation behavior underground during a substantial fire. Inertisation systems for handling underground fires, sealing of mine or mine sections, spontaneous combustion heatings and elimination of the potential explosibility of newly sealed gobs have been accepted as important safety approaches within the Australian industry.

Computer simulation of mine fires and effects on ventilation networks has been introduced to the Australian mining industry with considerable interest and success. This has put over 20 mines in an improved position in understanding of mine fires and the use of modern advances to preplan for fires and the handling of possible emergency incidents. The project has received substantial mine site and rescue organization support.

The study endeavored to increase understanding of behavior of mine fires in modern mine ventilation networks with the addition of inert gas streams. It also identified inertisation related modifications to the fire simulation software that have been undertaken by the Polish software authors. Three main areas are discussed. Inertisation systems in use and their characteristics are summarized. Issues in the successful application of the GAG jet engine inertisation method are identified after examination of application to various mine layouts. Issues in the use of surface boreholes connected to underground mine workings for delivery of inertisation gases are analyzed.

2 Inertisation Systems

Inertisation has been accepted to have an important place in Australian mining emergency preparedness. The two jet engine exhaust GAG units purchased from Poland by the Queensland government in the late 1990s for the Queensland Mines Rescue Service have been tested and developed and mines made ready for their use in emergency and training exercises. Their use in real and trial mine fire incidents has underlined the need for more information on their application (Gillies and Wu, 2006).

The NSW Mineshield (liquefied nitrogen) apparatus dates to the 1980s and has been actively used a number of times particular in gob heating incidents. The Tomlinson (diesel exhaust) boiler has been purchased by a number of mines and is regularly used as a routine production tool to reduce the time in which a newly sealed gob has an atmosphere “within the explosive range” and for gob spontaneous combustion headings. Nitrogen Pressure Swing Adsorption (Floxal) units are available and in use both for reducing time in which gobs are “within the explosive range” and for gob spontaneous combustion headings. Each of these facilities puts out very different flow rates of inert gases. Each is broadly designed for a different application although there is some overlap in potential usages.

Underground mine fires lead to complex interrelationships with airflow in the mine ventilation system (Gillies, Wala and Wu, 2004; Wala, 1996). Addition of the gas stream from an inertisation unit adds another level of complexity to the underground atmosphere behavior. Important questions are raised such as should the main mine fans be turned off so as not to dilute the inert gas or will this action cause, in conjunction with buoyancy effects, airflow reversal and the drawing of combustion products or seam gases across a fire leading to an explosion?

Summary details on the operational characteristics of these and other inertisation units are given in Table 1.

Various types of inertisation systems currently available and in use in Australian coal mines for elimination of the potential explosibility of newly sealed gobs, for combating gob spontaneous combustion headings, for sealing of old mine workings or for stabilizing fires in high priority locations have been examined. Systems have been compared to aid decision making in selection.

3 The GAG And Mine Ventilation Systems

The potential for simulation of the effects of inertisation on fires within a mine ventilation network was examined. The study involved applying the Ventgraph mine fire simulation software to preplan for mine fires. Work undertaken to date at some Australian coal mines is discussed as examples. The effort has been built around the modeling of fire scenarios in selected different mine layouts.

Case studies have been developed to examine usage of the GAG inertisation unit. One section examined seam gas emissions in the face area; addition of the inert gas stream adds another level of complexity to the already complicated interrelationships between the mine ventilation system, the presence of seam gases and a mine fire. Should the main mine fans be turned off to reduce dilution of the inert gas, or will this action cause, in conjunction with fire induced buoyancy effects, airflow reversal and the drawing of combustion products or seam gases across a fire leading to an explosion?

Another section has focused on selection of the surface portal location for placement of the GAG for effective fire suppression. The difficulties that some current approaches present are highlighted. The advantages that can be gained from use of various inertisation docking positions depends on a number of considerations including the location of the fire, the relative distance from the inertisation docking portal location and the attributes and complexity of the mine ventilation network. Operation of a GAG unit requires preplanning in terms of infrastructure requirements for a GAG surface portal docking station and access for operating personnel, fuel, water and other operating requirements.

Table 1 Characteristics in simplified form of the outlet flow of the GAG-3A, Mineshield, Tomlinson and Floxal inertisation units.

	Flue Gas Generator (Tomlinson Boiler)	Mineshield Liquid Nitrogen System	GAG unit	Membrane System (AMSA Floxal Unit)
Inert Output Range, m^3/s	0.5	0.2 – 4.0	14 – 25	0.12 – 0.7
Default Quantity, m^3/s	0.5	2.0	20	0.5
Delivery Temperature, °C	54	Atmospheric	85	20
Oxygen, %	2	0	0.5	3
Nitrogen, %	81.5	100	80 – 85	97
Carbon Dioxide, %	15.3	-	13 – 16	-
Carbon Monoxide, ppm	0	-	3	-
Water Vapor, %	1.2	-	some	-
Water droplets			significant	

Sources: Tomlinson Boilers, 2004; MinesShield, 2002/3; Bell, 1997; AMSA Floxal Unit, 2006.

Priority fire locations at a wide selection of mines with a developed and current Ventgraph simulation model have been examined as to the ability of a GAG inertisation unit to inert a fire in the mine recovery stage. In the study it was assumed that the GAG would be docked at a prepared position designated by the mine (most commonly the current fabricated docking installation). Many mine layouts were reviewed and from these 35 scenarios were considered appropriate for use of the GAG. These fires were categorized A to E in terms of ability of the GAG exhaust to effectively stabilize and extinguish the fire. As examples of results no fires met the category A description, 14 percent met category D and 20 percent met category E. The conclusion is that the current situation is not well placed to effectively inert most colliery priority fires.

These simulation exercises undertaken with a wide range of Australian mines focused attention to the situation that many potential underground mine fire sources cannot be successfully inertized with the GAG docked at the current specified point. This inability to deliver GAG output is particularly so for fires in extended areas of workings or in panels. Two important conclusions are

- Successful delivery of GAG output from units on the surface must consider other (that is alternative to Mains Travel or Conveyor Heading portals) delivery conduits directly into workings near the fire through existing or purpose drilled boreholes.
- During a fire the stopping of the main surface fan or fans will lead to rebalancing of pit ventilation and in some cases potential explosions through air reversals bringing poorly diluted exposable seam gases or fire products across the fire site.

Simulation of the introduction of the GAG or other apparatus has indicated that there is a substantial lack of knowledge on use of these facilities. The Queensland GAG units were first used actively in 1999 at the Blair Athol mine to handle a spontaneous combustion issue in old underground workings that were about to be mined by surface techniques (Prebble and Self, 2000). The GAG unit was subsequently used successfully in an underground mine fire at the Loveridge mine, West Virginia in early 2003 (Urosek et al, 2004). On this occasion the GAG ran for approximately 240 hours over 13 days and was successful in stabilizing the mine so that rescue teams could enter the mine and seal and fully extinguish the fire affected zone. Much was learnt about the ventilation network behavior and the need to have an upcast shaft open. Observations were made on the effects of natural ventilation pressure, barometric changes and rock falls on the backpressure experienced by the operating GAG.

A fire which was suspected to have been caused by lightening strike at the Pinnacle mine, also in West Virginia, was out of control from October 2003 to May 2004. A Polish owned GAG unit was successfully used to stabilize situation although there were a number of underground gas explosions during the course of the incident (Campbell, 2004). Following these experiences the US Micon company has purchased GAG units and has developed a commercial mine emergency and recovery business.

New and innovative approaches to mine recovery are occurring. In the US an equipment unit fire in the Dotiki mine, Kentucky, in early 2004 was stabilized using a Nitrogen and Carbon Dioxide (Wesley et al., 2006). Also in early 2004 carbon dioxide was used to stabilize a gob spontaneous combustion heating in the West Ridge mine in Utah (Stoltz et al., 2006).

Simulations with fire simulation software Ventgraph can be undertaken to gain better understanding of how inertisation units or systems interact with the complex ventilation behavior underground during a substantial fire or heating. Aspects worthy of examination include:

- Location of the introduction point for inert gases for high priority fire positions; eg. portal docking position, special boreholes;
- Size (diameter) of borehole or pipe range required to deliver inert gases and back pressure issues;
- Time required for inertisation output to interact with and extinguish a fire;
- Effects of seam gas on fire behavior with inertisation present;
- Changes which can be safely made to the ventilation system during inertisation including switching off some or all fans;
- Need for remote controlled underground doors to channel inert gases to the fire location;
- Complications caused by underground booster fans;
- Spontaneous combustion issues.

4 Effective Docking Positioning of Inertisation Units

Positioning of the inertisation units is a major determinant of potential success for most efficient suppression of a specific fire. Traditionally in Queensland docking points have been placed on intake ventilation headings. Some mines have prepared docking points on boreholes of about 1.0 to 2.0m diameter placed at the back of longwall panels.

The advantages that can be gained from use of various inertisation docking positions depends on a number of considerations including the location of the fire, the relative distance from the inertisation docking portal location and the attributes and complexity of the mine ventilation network. Operation of a GAG unit requires preplanning in terms of infrastructure requirements for a GAG surface portal docking station and access for operating personnel, fuel, water and other operating requirements.

A current ACARP supported project has been examining this aspect. Priority fire locations at mines with a developed and current Ventgraph simulation model have been examined as to the ability of a GAG inertisation unit to inert a fire in the mine recovery stage. In the study it was assumed that the GAG would be docked at a prepared position designated by the mine (most commonly the current fabricated docking installation.

A total of 71 potential priority mine fire locations that had had scenarios simulated were reviewed. From these 35 scenarios were considered worthy of incorporating utilization of the GAG. Table 2 shows results of the outcome of the 35 scenarios from the study.

Analysis of these situations leads to the following.

- Category A covers fire in which the inertisation product is directed fully over the fire. No mine priority fire examined achieved the situation in which the simulated fire is directly controlled to aid recovery in a timely manner.
- Category B covers situations in which the inertisation product goes straight to the fire but there is significant dilution from other ventilation air or leakage through stoppings. Some fan change needed to allow inertisation stabilization of fire. 20 percent of mines are in this category and under these situations the fire should, over time, be abated or stabilized to where conventional recovery approaches can be initiated.
- Category C covers priority fires in which the GAG output will never reach the fire location without stopping of one or more main surface fans to rebalance ventilation within the pit. In many of these cases requiring fan changes to put GAG output across the fire location effective ventilation air velocity has been reduced to the extent that local reversal across the fire occurs and fire fumes are pulled across the fire. This is an unsatisfactory situation as fire smoke and fumes can carry combustible products. This situation broadly prevails for 46 percent of the cases examined.

Table 2 Effectiveness of GAG delivery

Code	Description	Scenarios simulated	Percent %
A	GAG exhaust delivered efficiently (without significant dilution) to fire.	0	0
B	GAG exhaust reaches fire but diluted and not fully effective. Fan change needed to allow inertisation stabilization of fire.	7	20
C	GAG exhaust reaches fire only after fan change and potentially effective after local reversal of ventilation air (incl. fire fumes) across fire.	16	46
D	GAG exhaust will never reach fire even with fan changes.	5	14
E	GAG exhaust only reaches fire after fan change. Reversal of working section methane and ventilation air (incl. fire fumes) across fire.	7	20

- Category D covers priority fires in which the GAG output will never reach the fire location. These are fire locations within panel sections in which either the fire behavior stops normal intake ventilation flow into the section headings or the GAG docking point is in an airway that is segregated from the section. This situation is seen in 14 percent of the cases examined.
- Category E covers priority fires in gassy mines in which section production gas make has been included in the simulation modeling. GAG exhaust will never reach the fire location without stopping of one or more main surface fans to rebalance ventilation within the pit. However this change in ventilation causes working section methane and ventilation air (incl. fire fumes) to reverse across the fire. This is clearly a potentially dangerous situation. This situation was found in 20 percent of the cases examined.

These simulation exercises undertaken with a wide range of Australian mines focus attention to the situation that many potential underground mine fire sources cannot be successfully inertized with the GAG docked at the current specified point. This point is most commonly at the Mains Travel or Conveyor Heading portals.

This inability to deliver GAG output is particularly so for fires in extended areas of workings or in panels. Two important conclusions are

- Successful delivery of GAG output from units on the surface must consider other delivery conduits directly into workings near the fire through existing or purpose drilled boreholes.
- During a fire the stopping of the main surface fan or fans will lead to rebalancing of pit ventilation and in some cases potential explosions through air reversals bringing inadequately diluted explosible seam gases or fire products across the fire site.

5 Use of Boreholes for Delivery of Inertisation Gases

The potential use of appropriately sized boreholes to deliver inertisation output directly to a fire or heating has advantages. An analysis has been undertaken of design considerations for varying diameter and depth boreholes taking into account backpressure considerations inherent in fluid flow through relatively small diameter borehole airways. This exercise examines the relevant thermodynamic theory required to understand flow behavior in systems involving borehole delivery of GAG exhaust through docking to pre-drilled surface boreholes into underground workings. The study examines attainable designs for panel boreholes and how GAG docking to boreholes can improve delivery of GAG exhaust through a mine ventilation network.

Economic installation of well placed boreholes could allow the proactive use of larger inertisation units such as the GAG in a wider application in Australian mines responding to or recovering from mine fires or spontaneous combustion headings, the elimination of the potential explosibility of newly sealed gobs or in the making safe of old mine workings prior to final sealing.

Australian coal mines have experienced significant gob headings or gob fires in recent years. Incidents at mines such as Dartbrook in 2002 and 2005/06, Austar in 2003/04, North Goonyella in 2004/05 and Newstan in 2005/06 have caused significant loss of production time and in some cases mine reserves. Mine inertisation approaches relying on use of the Mineshield, Nitrogen Pressure Swing Adsorption (Floxal) and Tomlinson Boiler units have been used in these Australian recent mine incidents involving gob heating. The low output of 2 m^3/s or less of these units has limited their success. The GAG has the ability to supply a much higher output at an operating cost advantage but has not been considered to date for these applications due to inability to deliver the inert exhaust to the affected area.

There is potential for an increased role for the GAG built on experience gained in its use and other inertisation units in recent years. This can encompasses

- How GAG docking to boreholes can improve delivery of GAG inert gases to high priority potential fire locations particularly in working panels.
- How GAG docking to boreholes can be used to economically inert gob spontaneous combustion incidents. Small inert gas units have not been of sufficient capacity to handle major gob heatings in recent years.
- How GAG docking to boreholes can be used to inert gobs on sealing to avoid explosible atmospheres and movement of atmospheres "into the Explosibility Triangle".

Boreholes placed within panels or more remote areas of mine workings have the capability of being used to deliver inert gases to nearby fires and so aid in mine recovery. Since the early 1990s approaches to drilling of boreholes through the overburden overlying worked underground seams have improved significantly. Some major challenges with unstable strata have been overcome and a number of drilling companies service the market. Many collieries currently utilize one or more boreholes for ventilation, chilled air or road base delivery purposes. Boreholes can also be used for man escape.

The challenge faced is how to effectively design these holes economically. The GAG has capability of delivering an exhaust stream as measured from its outlet of about 20 m^3/s although some of this is water vapor that quickly drops out of the air stream. There are limits to delivery of GAG output through different diameter holes at varying depths. Deeper holes naturally require larger diameter openings to overcome back pressure. Some require very large diameter boreholes of greater that 1.5 m that are prohibitively expensive.

Inertisation exhaust flow in deeper or smaller diameter holes faces significant back pressure. Can jet engine thrust changes or an variable pressure fan that is placed in line with the GAG flow overcome substantial back pressure to allow holes of economical dimensions to be utilized?

A primary requirement is to examine attainable designs for panel boreholes under Australian conditions with current drilling technology. There is a limit to the contribution engine thrust changes or a variable pressure fan can make to assist flow. An objective will be to define

- Hole designs (diameters and depths) that can deliver directly without assistance of any fan,
- Hole designs that can deliver with assistance of a fan and the pressure required for this delivery to be attained, and
- Specifications of boreholes design parameters that cannot achieve delivery even with fan assistance.

Inertisation users in Australia and in particular GAG operators such as Mines Rescue organizations have expressed the need for answers to these questions for future planning. In particular detailed design parameters are needed by operating mines.

5.1 Understanding GAG Exhaust Fluid Behavior Down A Borehole

To investigate the possibility of using GAG in small diameter boreholes for either production inertisation or fire fighting purposes, it is necessary to understand GAG exhaust fluid behavior.

The GAG-3A jet engine has ability to deliver a thrust of approximately 10 kN. This is effectively a pressure delivery of about 2 MPa. The mine inertisation GAG jet is set up to operate safely with effectively no thrust This is achieved by allowing exhaust to exit the unit across the full flow section of the outlet and there is no contraction to build up pressure. This works well when the GAG is delivering into a large cross section mine airway which creates little backpressure. This can be considered as free flow from the isolated GAG engine.

The discussion that follows has been developed to illustrate in a simplified form the major aspects that need to be considered in delivering jet exhaust down a borehole or through any passageway that creates significant back pressure. One approach to the analysis has introduced a compressor fan to assist motivation of the flow through the borehole. However this could as effectively be achieved by harnessing some of the potential thrust that the jet is capable of delivering in its normal mode of doing "real work" in powering an aircraft.

The effects of super heating on the system varies with a number of conditions and needs further investigation.

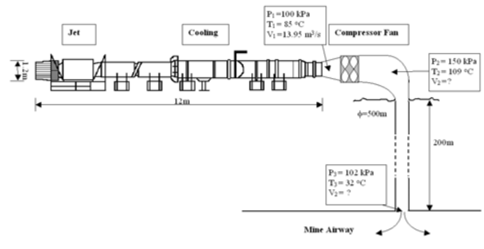

Figure 1 Schematic of GAG unit and compressor fan for borehole delivery.

Steady flow energy equation based on Bernoulli's equation made applicable to compressible flow can be put in a form to describe the behavior of GAG exhaust fluid being pushed down a borehole. Work needed to overcome resistance to flow exiting the GAG outlet can be evaluated as "Work to handle any issues of energy loss due to compression". In the example this is simplifies as work associated with passage through a compressor fan, work to overcome frictional rubbing drag on outlet walls, work to overcome shock losses, work to overcome elevation buoyancy effects and finally work to overcome water vapor super heating issues. Depending on the configuration of the outlet conduit these components may not all be additive. However in the system of passing GAG exhaust down mine boreholes all components will be additive. A systems involving borehole delivery of GAG exhaust is set out in Figure 1. The equation is of he form as shown.

$$W_{23} = \int_2^3 VdP + F_{23} + \left(\frac{u_2^2 - u_3^2}{2} \right) + (z_2 - z_3)g + \text{superheat}$$

where W_{23} = Work to achieve flow down the borehole, J/kg
VdP = Compression Work by compressor fan
F_{23} = Friction Impedance to fluid passing through pipe
u_2, u_3 = Fluid velocity terms, Shock loss
z_2, z_3 = Elevation terms
plus Superheated moisture energy.

(Superheated moisture energy may be important. This accounts for latent heat energy changes when steam is formed at the water boiling point (boiling point varies with the exhaust flow atmospheric pressure at the specific point). Superheated steam energy will be of greater importance under conditions when the exhaust mixture is forced through small diameter openings due to compression effects. This analysis has not gone into a detailed analysis of the mathematics of this energy transformation process).

5.2 The Fluid Under Analysis - GAG Output Behavior

Assume the GAG is operated at 7,200 rpm. From GAG operating information (Urosek, et al, 2004) as set down in Table 1, the GAG jet engine under free flow operating conditions will generate 13.95 m^3/s exhaust gas (0.5-2% O_2, 80-85% N_2, 13-19% CO_2) at 85°C and atmospheric pressure of 100 kPa. Under this situation there is a requirement for 5.48 kg/s inhaled air, a consumption of 17 liters per minute of Jet A1 fuel (s.g. 0.80 kg/m^3) and a mixing with the cooling water at a rate of 7.5 l/s (or 7.5 kg/s). A mass balance of the GAG system is as follows. Inputs to the GAG are

Air - 5.48 kg/s
Jet A1 fuel - 0.017 m^3/min ÷ 60s ×0.8 kg/m^3 = 0.23 kg/s
Mixed cooling water - 7.50 kg/s
Thus the total inputs mass is 13.21 kg/s.

Output from the GAG is 13.95 m^3/s at 85°C saturated conditions and atmospheric pressure of 100 kPa. Total output mass can be calculated by examination of psychometric properties as follows.

At outlet measurement point:
Saturated Vapor Pressure, P_{WS}
= 0.6105 Exp (17.23 × T_{WB}/(237.3 + T_{WB})
= 0.6105 Exp (17.23 × 85/(237.3 + 85)
= 58.04 kPa
Apparent Specific volume, ASV
= 287.23 × (T_{DB} + 273.15)/(P - P_{WS})
= 287.23 × (85 + 273.15)/(100,000 – 58,040)
= 2.45 m^3/kg
Mass flow of dry air, m_a
= 13.95/2.45
= 5.69 kg/s
True Density, ρ
= (P – 0.378 P_W)/(287.23 × (T_{DB} +273.15))
= (100,000 – 0.378 × 58,040)/(287.33 × (85 +273.15))
= 0.759 kg/m^3
Moisture content, r
= 0.622 × P_{WS}/(P - P_{WS})
= 0.622 × 58.04/(100,000 – 58,040)
= 0.860 kg/kg
Mass flow rate, m
= 13.95 × 0.759
= 10.58 kg/s

This mass flow includes approximately 5.69 kg/s of dry air and 4.89 kg/s of water vapor which is added by the direct contact of water for cooling of the exhaust gas. There is an imbalance of 13.21-10.58 = 2.63 kg/s in the system. This imbalance is caused by the excess liquid water droplets carried over in the exhaust (and into the mine) from the mixing cooling water. Therefore, a breakdown of the GAG exhaust gas is:

Exhaust gas - 5.69 kg/s
Water vapor - 4.89 kg/s
Excess water droplets carried over - 2.63 kg/s

The excess water droplets in the exhaust would in part be super heated under compression conditions during the GAG exhaust down a borehole. The following sections attempt to establish some understanding of the different components in the system delivering GAG exhaust down a borehole.

<u>To Establish Work Under Compression</u>

$$W = \int_1^2 VdP = R(T_2 - T_1)\frac{\ln\left(P_2/P_1\right)}{\ln\left(T_2/T_1\right)} \text{ J/kg}$$

Now from Figure 1, to establish Work change from Points 2 to 3 and assuming the use of a Compressor Fan of output = 50 kPa

If P_2 = 100 kPa (Atm) + 50 kPa (Comp Fan ΔP)
P_3 = 100 kPa (Atm) + (Pressure at depth)
R = Universal gas constant, 368.7

From General Gas Equation: $\frac{V_1}{V_2} = \frac{P_2}{P_1}\frac{T_1}{T_2}$ thus

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{1-\frac{1}{n}}$$

$$\therefore T_3 = (273+85)\left(\frac{150}{100}\right)^{1-\frac{1}{1.2}}$$

and assuming Polytropic Conditions n = 1.2

$$\therefore T_3 = 109°C$$

$$\int_2^3 VdP = 368(109-85)\frac{\ln\left(150/100\right)}{\ln\left(109/85\right)}$$

= 368 × (24 × 6.15)
= 54.31 kJ/kg

Work required is 54.31 kJ/kg × 10.62 kg/s = 576.77 kW

<u>Friction Impedance in Descending Borehole</u>

Assume Lines borehole ϕ = 500mm with a depth = 200m

Now pressure loss for compressed air in a pipe (or borehole) can be calculated by the following equation.

$$\Delta P = \frac{R_f \times m^2 \times L}{\rho} \times 10^{-3}$$

where R_f = resistance factor, m^{-5}
m = mass flow rate, kg/s
L = pipe length, m
ρ = air density, kg/m^3

ρ is calculated from average at top of shaft T_2 = 109°C, P_2 = 150 kPa and at bottom, T_3 = 32°C and P_3 = 100 kPa using the following equation.

$$\rho = \frac{P\times 10^3}{RT}$$

$$\rho = \frac{(150+102)/2\times 10^3}{368.7\times(382+313)/2}$$

= 0.987 kg/m^3

R_f for 500 mm pipe diameter is 0.36.

$$\therefore \Delta P = 0.36 \times (10.62)^2 \times 200 \times 10^{-3} \times \frac{1}{0.987} = 8.23 \text{ kPa}$$

$$\therefore F_{23} = m \times \Delta P = 10.62 \times 8.23 = 87.4 \text{ kW}$$

Work to overcome elevational buoyancy effects

Elevation buoyancy effects can be calculated by the following equation

$\rho g(Z_2 - Z_3) = 0.987 \times 9.81 \times (200) = 1{,}936.5$ Pa

Work to overcome Elevational buoyancy effects is
$10.62 \times 1.94 = 20.6$ kW

Shock losses for exit into mine

Shock Losses $= x\dfrac{v^2}{2g}(Pa)$

Assume hole (entry and exit) $x \approx 1.0$

Q = 5.2 m^3/s at exit (at 32°C, density of 1.143 kg/m^3 and with majority of moisture already having dropped out)

$$Vel = \frac{5.2}{\pi r^2} = \frac{5.2}{\pi \times 0.25^2} = 26.3\, m/s$$

Assume $x = 1.0$

$$\therefore Shock = 1.0 \times \frac{26.3^2}{2 \times 9.81} = 35.3 Pa$$

$$\therefore Work = \frac{1}{\rho} \times 10.62 \times 0.035$$

$$\therefore Work = \frac{1}{1.143} \times 10.62 \times 0.035$$

$= 0.33$kW

Therefore, compressor fan would be required to input the follow work

$$W_{23} = \int_2^3 VdP + F_{12} + \left(\frac{u_2^2 - u_3^2}{2}\right) + (z_2 - z_3)g + \text{superheat}$$

The first four terms in the equation as worked out above are

$W_{23} = 576.8 + 87.4 + 20.6 + 0.33 = 685.13$ kW

Thus delivery of 13.95 m^3/s GAG exhaust down a 200 m borehole of 500mm in diameter would require at least 700 kW of energy without consideration of the super heating component.

5.3 Flow Through Various Borehole Designs

Inertisation exhaust flow through deeper or smaller diameter holes faces significant backpressure. A variable pressure fan placed in line with the GAG flow could overcome substantial backpressure to allow holes of economical dimensions to be utilized.

A primary requirement is to examine attainable designs for panel boreholes under Australian conditions with current drilling technology. Part of this is to calculate design considerations for a variable pressure fan that can assist flow against backpressure. There is a limit (assumed up to 50 kPa) to the contribution a variable pressure fan can make to assist flow. Dziurzyński, (2004) stated that the GAG could operate continuously against a backpressure of 2 kPa.

From calculations it can be seen that if the borehole diameter is 800mm, the GAG can deliver 15 m^3/s of exhaust without assistance of a compressor fan to overcome the backpressure from the borehole for up to 100 m in borehole depth. However some fan assistance is required for the borehole depths in excess of 100 m.

For 500 mm borehole, it could deliver 15 m^3/s of exhaust for borehole depth up to 350 m with compressor fan assistance. When the borehole depth is more than 350m, it is not able to deliver 15 m^3/s of exhaust even with fan assistance but it is possible to deliver a lesser amount of exhaust of 10 m^3/s.

Borehole design parameters have been established applicable to Australian conditions based on the complex fluid flow theory that describes the dynamic, hot, pressurized exhaust carrying a superheated vapor. Determinations have been made of the relationships between borehole back pressure and GAG thrust relationships and the best approach to vary the jet engine thrust to overcome this bask pressure. These mathematical relationships can be applied to investigate the possibility of using GAG in small diameter boreholes for either production inertisation or fire fighting purposes.

GAG operations are very situation specific. For its use careful consideration of the following is required;

- Time to inertize area,
- Effective dilution rates and flows.

The back analysis of the air flow monitored data during part sealing of the 2005 Newlands South workings (without a fire present) showed that a Ventgraph model could be established to simulate satisfactorily this incident. The inertisation exercise highlighted a number of findings.

- The GAG quantity measured exhausting from the mine area being sealed was at first considered to be unrealistically low compared with nominal unit output. However further analysis, as detailed above, indicated that accounting for temperature and moisture mass changes explains any differences. The GAG jet exhaust (as with any combustion exhaust) puts out a lot of moisture and the cooling water usage adds a lot more. This exhaust product flow mass is lost from the system as it condenses and "wets" the mine workings. Temperature reductions lead to no mass change but "lower" quantity measured.
- The hypothesis that some of the GAG exhaust, with diurnal pressure changes within the workings, will flow into and out of gobs is of interest. This is very likely and means that gob voids should be taken into account in calculating mine excavation volume and that the cyclic pattern of this in and out flow needs to be accounted for.

Further monitoring of mine site GAG exercises are warranted to give greater understanding to this complex system.

6 Conclusions

Mine fires and headings are recognized across the world as a major hazard issue. New approaches allowing improvement in understanding their use of inertisation techniques have been examined. The outcome of the project is that the mining industry is in an improved position in their understanding of mine fires, use of inertisation and the use of modern advances to preplan for the handling of possible emergency incidents.

A study has examined the potential for simulation of the effects of inertisation on fires within a mine ventilation network. The project involved applying the "Ventgraph" mine fire simulation software to preplan for mine fires. Work undertaken to date at some Australian coal mines is discussed as examples. The effort has been built around the modeling of fire scenarios in selected different mine layouts.

Case studies have been developed to examine usage of inertisation units and particularly application of the GAG unit. One section has focused on selection of the surface portal location for placement of the GAG for effective fire suppression. The difficulties that some current approaches present are highlighted. Another section has looked at issues involved with delivery of GAG output through boreholes. These present a complex ventilation network and with additional interference from a fire, maintaining control of the movement of inert gas is more difficult than elsewhere in the mine.

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