

Proceedings of the workshop
on
Principles and Modeling of Underground Mine
Ventilation Systems

Organized by
Minerals, Metals and Materials Technology Centre (M3TC)



August 3, 2012

Workshop Schedule

Principles and Modeling of Underground Mine Ventilation Systems

Organized by

Minerals, Metals and Materials Technology Centre (M3TC)

Chair: Dr. Erik Birgersson, Department of Chemical & Bio-Molecular Engineering, NUS, Singapore

Co-Chair: Dr. Poh Hee Joo, Institute of High Performance Computing, A-Star, Singapore

Date : Friday, 3 August 2012

Time : 08.45 am – 12.30 pm

Venue : Faculty of Engineering, National University of Singapore (Room EA-06-03)

Program

08.45 - 09.00	Registration		
09.00 – 09.10	Introduction	Prof Arun S Mujumdar	Department of Mechanical Engineering and M3TC, NUS
09.10 - 09.50	Mathematical multi-scale framework for total air-conditioning in underground mines	Dr. Erik Birgersson	Department of Chemical & Bio-molecular Engineering and M3TC, NUS
09.50 – 10.20	Best practice for methane and dust control in underground coal mine	Jundika C. Kurnia	Department of Mechanical Engineering and M3TC, NUS
10.20 – 10.40	Coffee Break		
10.40 – 11.10	Thermal management in underground coal mines	Karthik Somasundaram, Dr. Agus P. Sasmito	Department of Mechanical Engineering and M3TC, NUS Masdar Institute of Science and Technology
11.10 – 11.40	Control of methane and dust related hazards in coal mines	Jundika Candra Kurnia	Department of Mechanical Engineering and M3TC, NUS
11.40 – 12.10	Modeling of coal dust and use of water sprays to control dust/emissions	Dr. Poh Hee Joo	Institute of High Performance Computing, A-Star
12.10 – 12.30	Open Discussion		



Mathematical multi-scale framework for total air-conditioning in underground mines

Agus P. Sasmito, Ly Cam Hung, Erik Birgersson, Arun S. Mujumdar

Minerals, Metals & Materials Technology Centre (M3TC)
National University of Singapore, Singapore

NUS, August 2012

- Introduction to underground mining:
 - History
 - Underground structures
 - Underground equipment
 - Hazards
- Total air-conditioning:
 - Overview
 - Quality control
 - Quantity control
 - Temperature-humidity control

- Mathematical modeling:
 - Overview
 - Objectives
 - Multi-scale and -physics
 - Verification and validation
 - Model reductions
- Automated code generation:
 - COMSOL Multiphysics
 - Matlab script
 - Examples
- Conclusions & outlook

Introduction

History

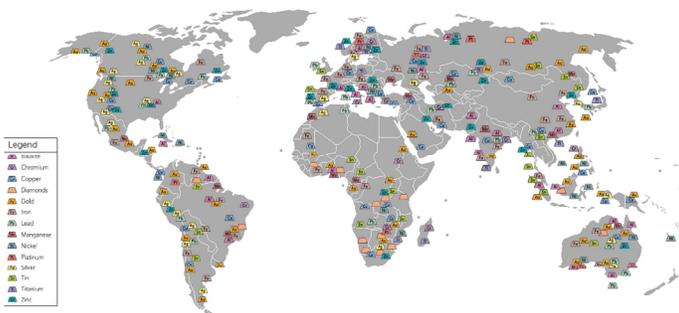
- Mankind has extracted materials from the earth since prehistoric times
- Mining is the extraction of minerals/materials from the earth
- Stones, metals, coal, diamonds, rock salt...
- Oldest known mine:
 - “Lion cave” in Swaziland
 - around 43000 years old
 - Mined iron-containing mineral hematite
 - Ground and produced red pigment
- Two main different types:
 - Open-pit (most predominant)
 - Sub-surface (underground)
- Shift towards underground mining in future



<http://explo.com/miners; wikipedia>

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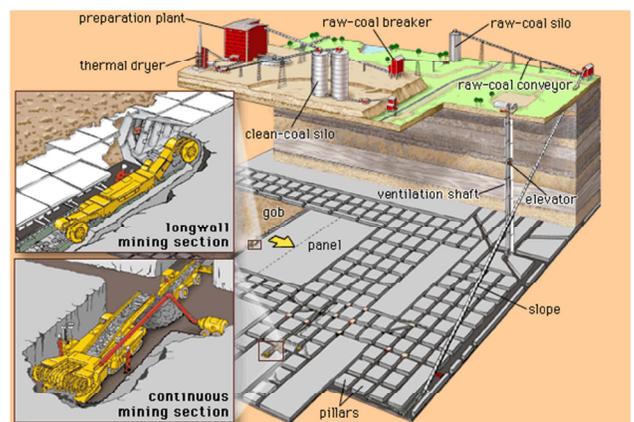
Mines across the globe



Wikipedia

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Underground structures



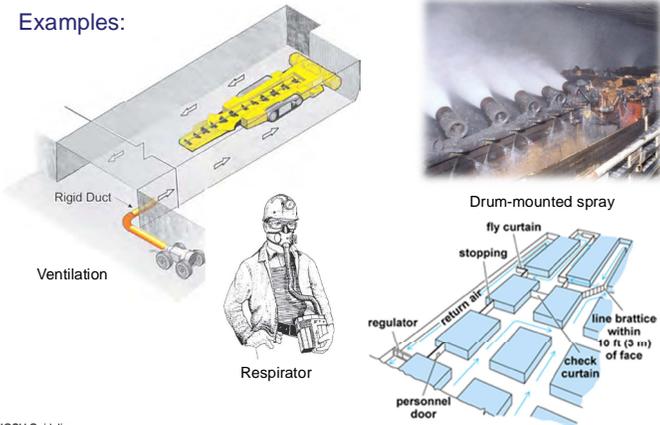
<http://www.britannica.com/EBchecked/media/113913/Schematic-diagram-of-an-underground-coal-mine-showing-surface-facilities>

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Underground equipment



Examples:



NIOSH Guidelines
H. L. Hartman et al., Mine ventilation and air conditioning, 3rd ed. (1997)

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Hazards



- One of the most dangerous working environments
- Fire
 - Defective bearings
 - Internal combustion engines
 - Explosives and detonators
 - Burning, welding
 - Electrical and mechanical machinery and equipment
 - ...
- Flood
- Collapse
 - Induced seismicity
 - Explosives might cause earthquake-like events
 - Dust or gas explosions
 - Timbering/pillar failure
 - ...

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Hazards



- Toxic contaminants
 - Dust
 - Aerosols,
 - Diesel fumes (carbon dioxide)
 - Gases from the rock (e.g. methane)
 - ...
- Explosions
 - Methane
 - Coal dust
 - ...
- Blasting related hazards
 - Explosive fumes
 - Misfires
 - Premature blasts
 - ...

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Total air-conditioning

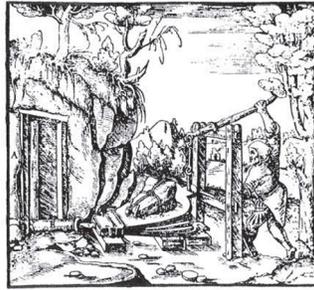


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Overview



- Simultaneous control of the environment
- Three main components:
 - Quality control
 - Quantity control
 - Temperature-humidity control
- Design of total air-conditioning:
 - Starts at the planning stage of the mine
 - Type of mine
 - Production rate
 - Infrastructure
 - Rules of thumb



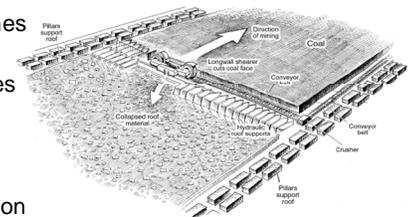
A—TUNNEL. B—PIPE. C—NOZZLE OF DOUBLE BELLOWS.

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Overview



- Revisions due to the dynamic nature:
 - After the mine has been in operation some time
 - New production zones established
 - Old production zones depleted
 - New stoppings introduced
 - Changes to ventilation system



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Quality-control



- Purification of air and removal of contaminants
- To keep non-particulate and particulate contaminant concentrations below thresholds
- Typical non-particulate gases:
 - Oxygen (from air)
 - Nitrogen (from air)
 - Carbon dioxide (from combustion engines)
 - Methane (rock strata)
 - Hydrogen sulphides (rock strata)
- Typical particulate contaminants:
 - Dust
 - Fumes
 - Smoke

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Quantity control



- Regulation of magnitude and direction of airflow
- Concerns ventilation in the form of:
 - Tunnels
 - Shafts
 - Rooms in the mine
 - External fan intakes/exhausts
 - Auxiliary fans dispersed through the mine
 - ...



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Temperature-humidity control



- Provides comfort air conditioning
- Allow humans to breathe and function more easily



www.sciencephoto.com

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Mathematical modeling

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Overview



- Currently:
 - “Full” models only for small parts of a mine
 - “Reduced” models for parts or entire mine, based on network theory (similar to electric equivalents)
 - Rules of thumb predominant
- Our approach:
 - Capture relevant physical phenomena with high geometric resolution
 - Scaling analyses justify reductions
 - Verification (Fluent) and experimental validation
 - Automated code generation

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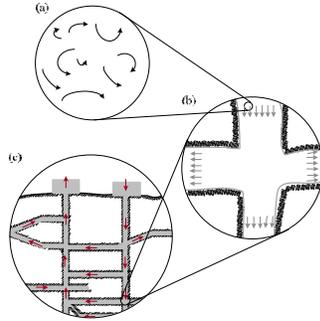
Objectives



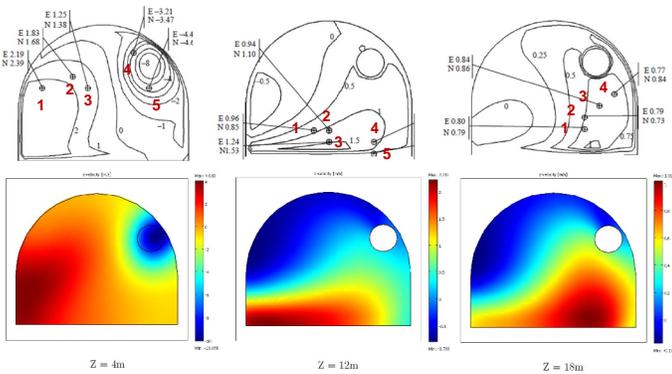
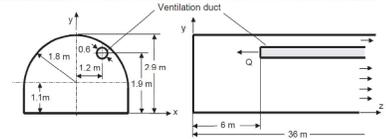
- Automated design of total air-conditioning during the various stages of a mine
- Multi-scale and multi-physics
- Fast and easy to use
- Cost effective application
- Innovation
- Risk analysis
- Optimization
- Generic (easily extended)
- Open source (in future)

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- Simplifications
 - Rock strata reduced to boundary conditions
 - ...
- Conservation of
 - Mass
 - Momentum
 - Species
 - Energy
- Fan models
- Turbulence models:
 - Spallart-Almaras
 - k-epsilon
 - k-omega
 - Reynolds stress model



- Cul-de-sac
 - High-risk area
 - Dead end
 - Accumulation of methane and other pollutants
 - Requires ventilation
 - Well-studied case
 - Similar length scale to the geometries considered



	Experimental Results	Numerical Result	Error (%)
Z = 4		k-ε model	k-ε model
Point 1	2.2	2.3	6.1
Point 2	1.8	1.7	6.1
Point 3	1.3	1.67	33
Point 4	-3.2	-1.9	41
Point 5	-4.4	-5.5	25
Z = 12			
Point 1	1.0	1.4	45
Point 2	0.94	1.4	52
Point 3	1.2	1.8	43
Point 4	1.0	1.2	21
Point 5	0.90	1.3	40
Z = 18			
Point 1	0.8	0.94	17
Point 2	0.79	0.85	8.1
Point 3	0.84	0.76	9.7
Point 4	0.77	0.52	32

- 3D reduced models:
 - Critical parts and overall network
 - Full geometrical resolution
 - Type of governing equations reduced
 - e.g. turbulent flow reduces to a second-order PDE with source terms accounting for wall friction etc.
 - Ok for overall network but not critical parts

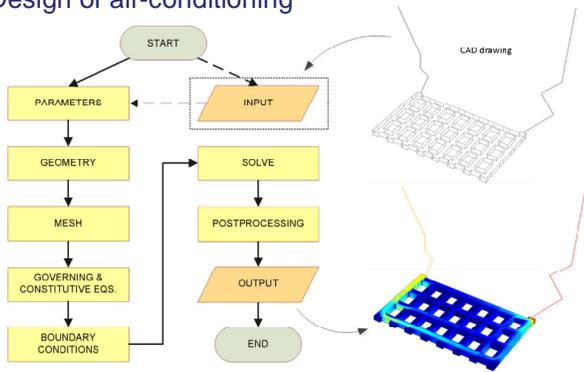
- 2D reduced model:
 - Directional derivatives are considered
 - Representative cross-sections (planes) in 3D networks
- 1D reduced models:
 - Directional derivatives in streamwise direction
 - Representative lines of the 3D network
 - Similar to network models
 - Coupled with fully resolved 3D models for critical regions

$$\frac{P_{out} - P_{in}}{L} = -\frac{1}{2} \frac{\rho f}{D_h/4} v^2$$

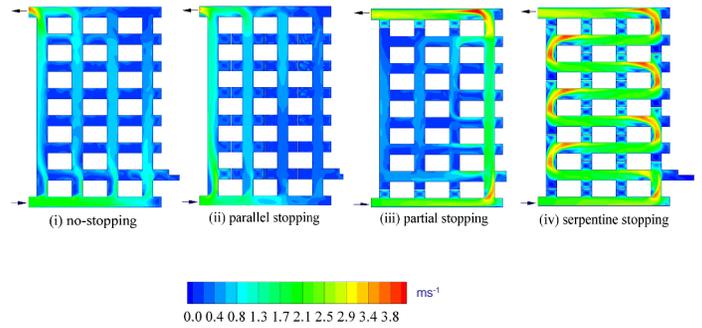
Automated code generation

- Commercial finite-element solver
 - Arbitrary differential equations:
 - Non-linear
 - Coupled
 - Mix of algebraic, ordinary and partial
 - Bi-directional interfaces
 - Open
- Comsol Multiphysics**
- Technical computing language
 - Mature
 - Numerical analysis:
 - Math, statistics and optimization
 - Easy-to-use
 - Post-processing
 - Data visualization
- Matlab**

• Design of air-conditioning



• Design of flow stoppings



Conclusions & outlook

- Overview of underground mining
- Total air-conditioning
- Mathematical modeling
 - Multi-scale and multi-physics
 - Turbulent flow
 - Dynamic (changes as the mine ages)
- Automated code generation
- Demonstration with a few examples

- Extend to account for more physics
- Statistical analysis (random events, probability of hazards)



Best practice for methane and dust control in underground coal mine

Jundika Candra Kurnia

Minerals, Metals and Materials Technology Center
National University of Singapore



Singapore, August 2012



Outline

- Overview of underground coal mine
- Hazards in underground mine
- Mine ventilation
- Methane control
 - Monitoring methane level
 - Controlling methane on the mining face
- Dust control
 - Monitoring dust
 - Controlling dust on the mining face
- Summary

Overview of underground coal mines

- Coal availability:
 - Most coal seams are too deep underground for opencast mining
 - UG mines currently accounts for about 60% of world coal production.
 - Coal in surface mines is decreasing
- Underground miners confront a **hostile environment** that they must depend on **mine ventilation**
- The presence of methane gas, coal dust, oxygen and heat can trigger explosion and /or health issues for miners
- Several accidents with fatalities have received attention all over the world.



Methods of underground coal mining

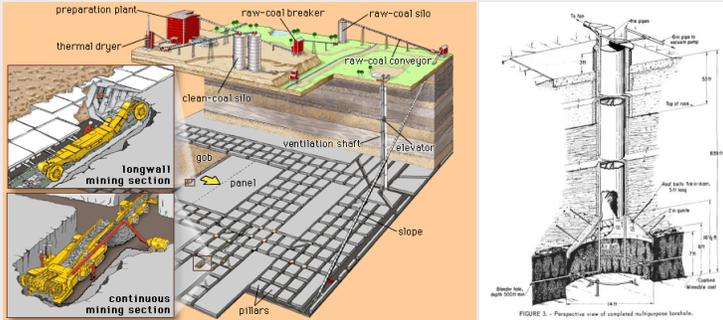
Mining Method



- **Longwall mining**- is a form of underground coal mining where a long wall of coal is mined in a single slice.
- **Continuous mining** (also called room and pillar)- is a mining system in which the mined material is extracted across a horizontal plane while leaving "pillars" of untouched material to support the overburden leaving open areas or "rooms" underground.
- Others:
 - Blast mining
 - Deep-vein mining
 - Vertical crater retreat mining,
 - etc



Underground coal mine structure



Typical underground structure: longwall and room and pillar mines



<http://www.bdtaprica.com/EE/checked/medial/113013/Schematic-digram-of-an-underground-coal-mine-showing-surface-facilities>
<http://accessscience.com/content/C0a7k20mining7143500>

Hazards in underground coal mining

- Structural/geological hazards
 - Rib/roof failure
 - Failure of supported ground
 - Pillar failure or collapse
- Mine gases hazards
 - Oxygen depletion
 - Methane
 - Carbon monoxide, etc...
- Chemical hazards
 - Coal dust
 - Crystalline silica
- Machinery/equipment hazards
- Physiological hazards

Methane and dust control



METHANE CONTROL



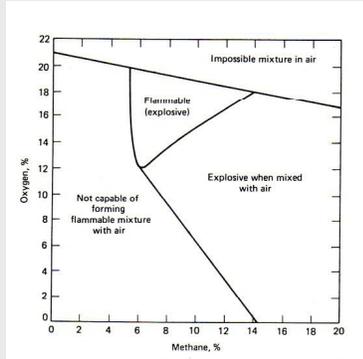
Methane emission from mines

- Methane is consistently found in underground coal reserves.
- The deeper the coal, the higher the pressure and the greater amounts of methane can be found.
- Methane is a significant cause of mining disasters around the globe.
- Most explosions in coal mines occur when an explosive methane-air is present
- Mine safety regulations require underground coal mines to assure that methane concentrations in the mine workings are maintained at safe levels (below explosive level)



Explossibility of methane

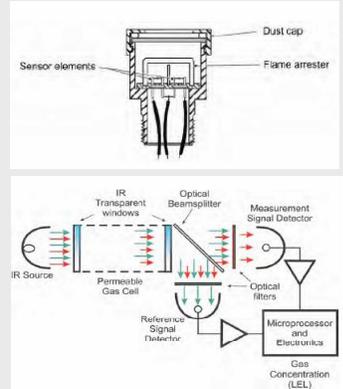
- Lower explosion limit of methane-air mixtures, which under normal conditions is 4.4% CH₄
- US law regulate maximum methane concentration of 3% or greater than 20% with oxygen concentration less than 10%
- In Germany, max allowable methane concentration is 1%, UK 1.25%, France 2%, Spain 2.5%



K. Noack, International Journal of Coal Geology 35 (1998) 57-82

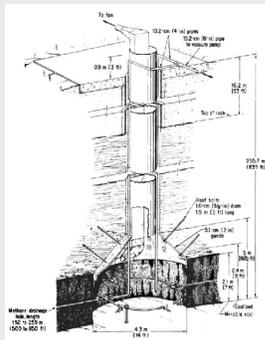
Methane monitoring in underground mines

- Methane detectors basic principle:
 - A catalytic heat of combustion sensors (methane below 8% and air above 10%)
 - Infrared absorption sensor (0% oxygen up to 100% methane)
- Classification
 - Portable (methane detectors)
 - Machine mounted (methane monitors)
- Flow meter



Methane control in underground mines

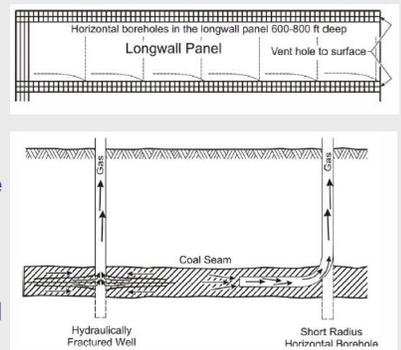
- Before excavation:
 - Pre-mining drainage
- During excavation:
 - Fresh air ventilation
 - Water spray
 - Inert ventilation
 - Scrubber ventilation
- After excavation:
 - Inertisation,
 - Post-mining drainage
- Lean air-methane mixture can be collected in the surface and utilized for catalytic combustion to produce energy



K. Noack, International Journal of Coal Geology 35 (1998) 57-82

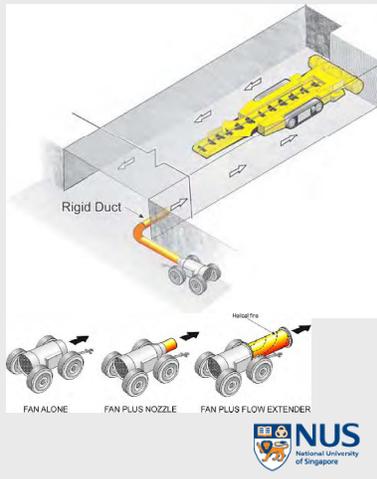
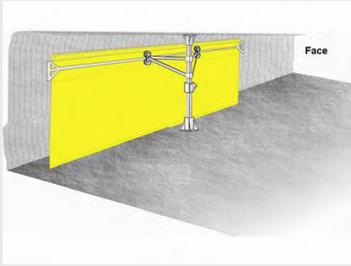
Pre-mining drainage

- Horizontal in-seam
- In-mine vertical or inclined (cross-measure) boreholes in the roof and floor
- Vertical wells that have been hydraulically fractured (so-called frac wells)
- Short-radius horizontal boreholes drilled from surface

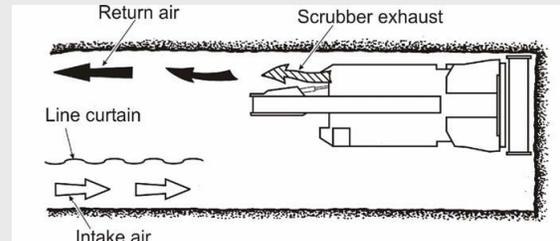


Fresh air ventilation

- Blowing ventilation with additional fan
- Exhausting ventilation with additional fan
- Brattice ventilation

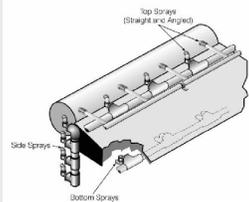
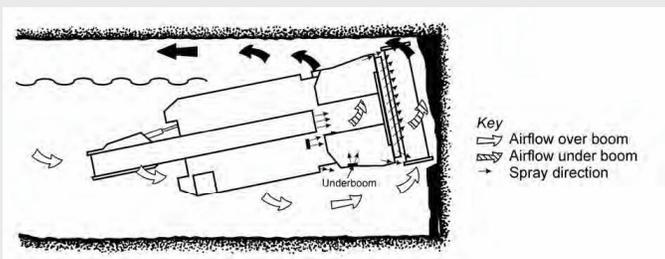


Scrubber ventilation



- Scrubber moves a large quantity of air in the face area
- This air movement can improve the dilution and removal of methane gas from the face area

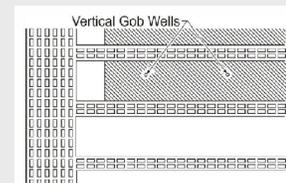
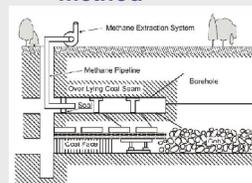
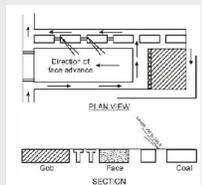
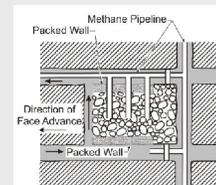
Water spray



- Act as small fans and move air
- Helps dilute and remove methane from the face area
- It can be grouped to direct airflow across the mining face

Post-mining drainage

- The packed cavity method and its variants
- The cross-measure borehole method
- The superjacent method
- The vertical gob well method

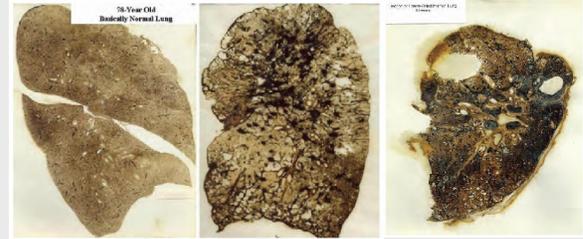


DUST CONTROL



Dust emission in underground coal mining

- Cause serious health problem for miners (CWP, silicosis)
- Proper dust control is required
- Surveys revealed that respirable dust levels in the last open crosscut can be as high as 0.42 mg/m^3 *
- Higher air velocities in the intake entries may result in increased dust entrainment if proper controls are not applied



*Rider JP, Colinet JF [2007]. Current dust control practices on U.S. longwalls. In: Proceedings of Longwall USA (Pittsburgh, PA, June 5-7, 2007).



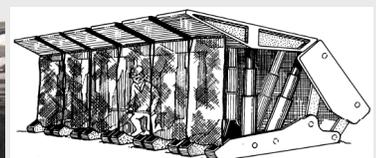
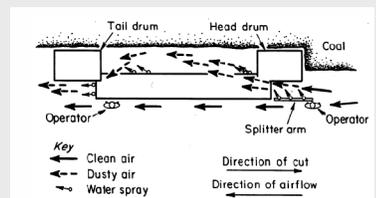
Dust monitoring in underground coal mines

- Gravimetric sampler → weight of dust
- Personal DataRAM (pDR) → light scattering
- Personal dust monitor (PDM) → tapered-element oscillating microbalance



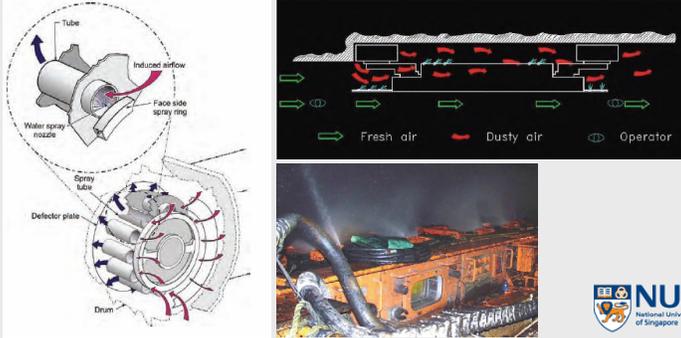
Dust control in longwall mines (Shearer 1)

- Face ventilation
 - Blowing
 - Exhausting
- Face curtain
- Shearer deflector plate



Dust control in longwall mines (Shearer 2)

- Drum-mounted spray system, full-cone sprays are the most effective type of spray pattern to use in shearer drum.
- Cutting drum bit maintenance
- Directional water spray system (Headgate and tailgate)



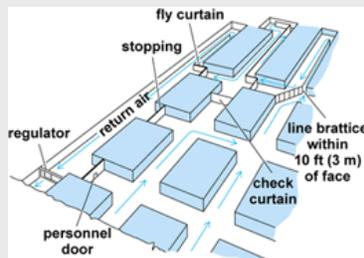
Dust control in longwall mines (Shearer 3)

- Keeping the headgate splitter arm parallel to the top of the shearer
- Crescent sprays
- Air dilution
- Unidirectional cutting
- Foam discharge from cutting drum

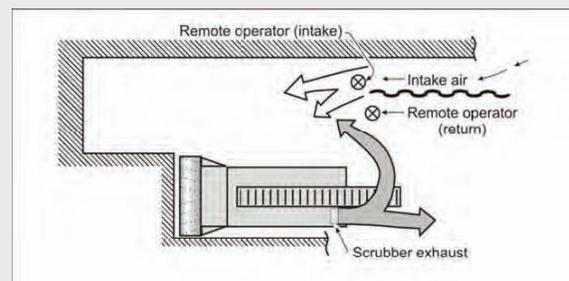


Dust control in continuous mine operations

- Blowing face ventilation
- Exhausting face ventilation
- Proper bit design and maintenance
- Modified cutting method
- Water spray system
- Flooded-bed scrubbers

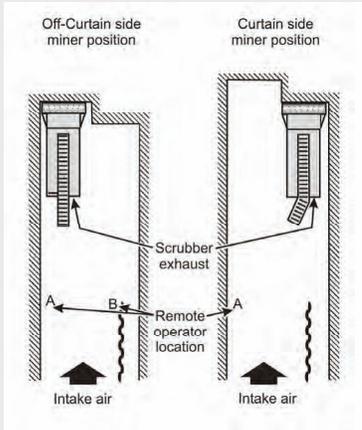


Blowing face ventilation



- Operator positioned in the mouth of blowing
- Scrubber discharge must be on the opposite of the line brattice
- Brattice discharge >800 fpm have better penetration and dilution of dust and methane

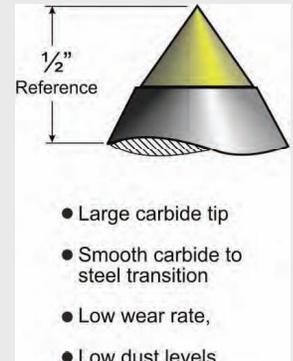
Exhausting face ventilation



- Give more possibility for the operator to avoid dusty air
- Shuttle car operator are always in fresh air
- Scrubber exhaust must be on the same side with the exhaust curtain

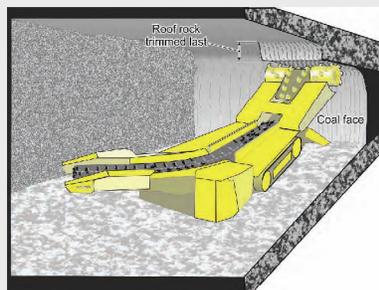
Proper bit design and maintenance

- Bit type and wear significantly affect the dust production
- Routine inspection and maintenance are required to ensure optimum cutting
- Bits with large carbide inserts and smooth transitions produce less dust during cutting operation
- Worn bits produce more dust

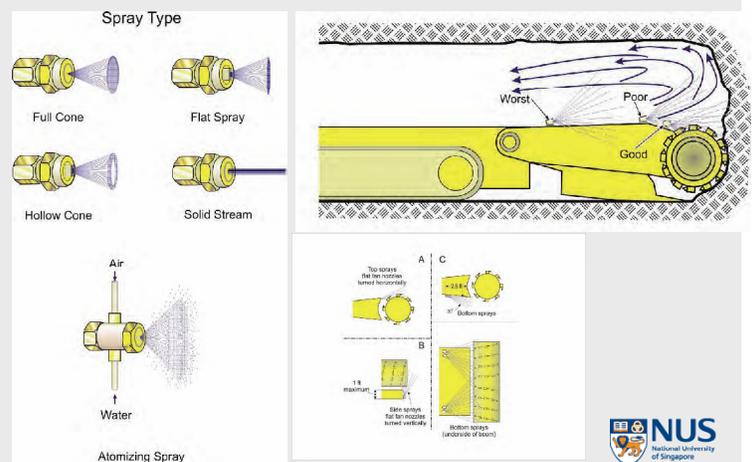


Modified cutting method

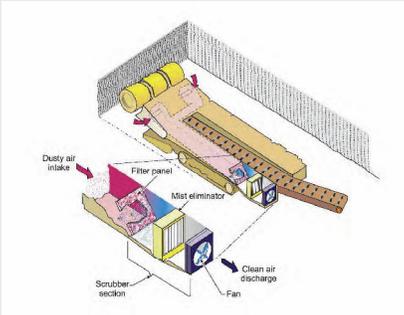
- If roof rock must be cut, it is often beneficial to cut the coal beneath the rock first and then back the miner up to cut the remaining rock
- This method of cutting leaves the rock in place until it can be cut out to a free, unconfined space, which creates less respirable dust



Water spray system



Fllooded-bed scrubbers



- Scrubber maintenance (one-third after one cut)
- Airflow measurement
- Use of surfactants
- Redirected scrubber discharge

Respirator for miner

- Half-mask replaceable-filter respirators
- Dust masks
- Air helmets



Dust control summary

DUST CONTROL METHOD	EFFECTIVENESS (Low is 10%-30%, moderate is 30%-50%, high is 50%-75%)	COST AND DRAWBACKS
Dilution ventilation	Moderate	High – more air may not be feasible
Displacement ventilation, including enclosure with extraction of dusty air	Moderate to high	Moderate – can be difficult to implement well
Wetting by sprays	Moderate	Low – too much water can be a problem
Airborne capture by sprays	Low	Low – too much water can be a problem
Airborne capture by high pressure sprays	Moderate	Moderate – can only be used in enclosed spaces
Foam	Moderate	High
Wetting agents	Zero to low	Moderate
Dust collectors	Moderate to high	Moderate to high – possible noise problems
Reducing generated dust	Low to moderate	Moderate
Enclosure with sprays	Low to moderate	Moderate
Dust avoidance	Moderate	Low to moderate

Summary

- Overview of underground mine:
 - Mining methods
 - Mine structures
 - Hazards in underground mines
- Methane control
 - Pre-mining
 - During mining/excavating
 - Post-mining
- Dust control
 - Water spray
 - Ventilation
- Further study is needed to improve methane and dust control

Further reading

- HL Hartman, JM Mutmanský, RV Ramani, YJ Wang, 1997, Mine ventilation and air conditioning, New York: Wiley.
- FN Kissel, 2006, Handbook for Methane Control in Mining, National Institute for Occupational Safety and Health.
- CD Taylor, JE Chilton, GVR Goodman, 2010, Guidelines for the Control and Monitoring of Methane Gas on Continuous Mining Operations, National Institute for Occupational Safety and Health.
- K Noack, 1998, Control of Gas Emission in Underground Coal Mines, International Journal of Coal Geology, Vol 35, pp 57-82.
- FN Kissel, 2003, Handbook for Dust Control in Mining, National Institute for Occupational Safety and Health.
- JF Colinet, JP Rider, JM Listak, JA Organiscak, AL. Wolfe, 2010 Best Practices for Dust Control in Coal Mining.



Thermal Management in Underground Coal Mines

A.P. Sasmito, E. Birgersson, A.S. Mujumdar and S. Karthik

Minerals, Metals & Materials Technology Centre (M3TC)
National University of Singapore
Singapore

Singapore, August 2012

- Background
- Model development
- Validation
- Results and Discussion
- Concluding remarks

2

Why underground mines?

- Coal and other natural resources availability in surface mines is decreasing (next 10 to 20 years)
- SEA has abundant underground coal and other natural resources (~100 – 3000 m below surface).
- Underground mining cost less expensive than surface mining if environmental cost is taken into account*.
- Environmentally friendly, i.e., mines below cities, protected forest area etc

3

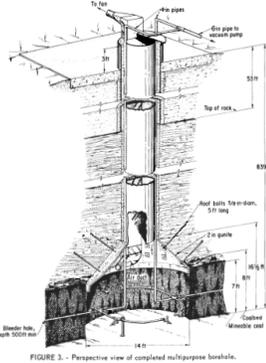
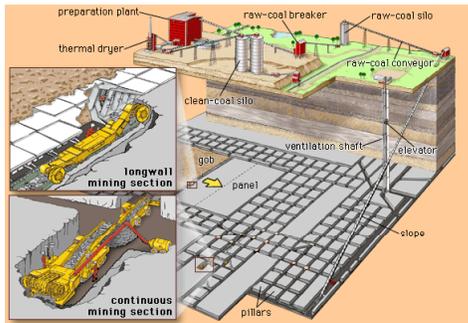
*Poland mining institute studies

Challenges:

- Need **advanced technologies** – never too late to start R&D: academic, government and industries!!!
- Manpower issues
- **Safety issues:** several accidents with fatalities all over the world.
 - Structural collapse
 - Fire/explosion
 - Health problem
- Productivity
- High operating **cost**.

4

Typical underground structure: longwall and room and pillar mines



5

<http://www.britainia.com/EEcheckedimg/113013/Schematic-diagram-of-an-underground-coal-mine-showing-surface-facilities>
<http://accessscience.com/content/Coal%20mining/143500>

- Fire/explosion prevention
 - Methane control
 - Dust control
 - **Thermal management**
- Miners health
 - Oxygen control
 - Humidity control
 - Diesel emission management

Recent major coal mine explosion incidents

Country	Date	Coal mine	Number of fatalities
China	14 Feb 2005	Sunjawan, Haizhou shaft, Fuxin	214
Kazakhstan	20 Sep 2006	Lenina, Karaganda	43
USA	2 June 2006	Sago, West Virginia	12
Russia	19 March 2007	Ulyanovskaya, Kemerovo	108
Ukraine	19 November 2007	Zasyadko, Donetsk	80
China	November 2009	Heilongjiang	104
USA	5 April 2010	Upper Big Branch, Montcoal, West Virginia	38
Russia	8 May 2010	Raspadsckaja, Mezhdurechensk	66
New Zealand	19 Nov 2010	River Pike	29
Columbia	26 Jan 2011	La Preciosa, Sardinata	21
Pakistan	20 March 2011	Sorange district of Pakistan	45
USA	5 April 2011	Upper Big Branch, Montcoal, West Virginia	38
Ukraine	29 July 2011	Suhodolskaya-Vostochnaya coal mine	19
China	29 October 2011	Xialichong mine in Hengyang of Hunan province	29

7

Why thermal management

- Underground temperature can rise significantly up to 80 degC – depending on several factors.
- Affect health of miners: heat stroke, long term health issues, etc
- Affect mining productivity.
- Some underground mining, but not coal mines, (for example, underground gold and copper mines in Indonesia, PT Freeport in West Papua) have lower underground temperature than surface temperature; thus heating is needed

8

Coal mine	Depth (m)	Rock temperature (C)
Amandelbult, South Africa	3300	55
Fengyu-Lead, Japan	500	80
Sanhejian, China	1300	56
Jiahe, China	800	32-34
Zhangshuanglou, China	1000	34-36
Zhangxiaolou, China	1125	30
Jisan, China	785	31.51
Wobei, China	640	35-36
Yongchuan, China	800	29.3-31.5
Baiji, China	700	Summer is 2-3 C hotter than winter
China, north vs south	1000	South temperature is around 1.5 times higher (>45 C) than that of the north (35 - 45 C)
Wu Tongzhuang, China	-	41

- As mine delve deeper into the earth, **temperature can rise significantly** up to 80 degC, in some cases it reaches 56 degC at a depth 1300m.
- The **relative humidity** at working environment is usually up to 90 – 100%
- Comfort environment for miners ~30C
- Chilling is required!!!**

9

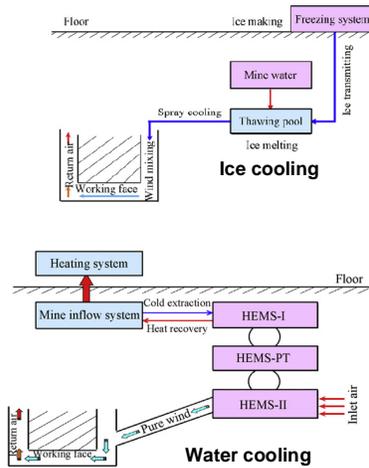
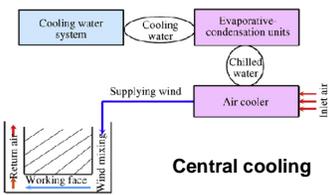
Y. Xiaojie et al. / Mining Science and Technology (China) 3 (2011) 1-5

- Climate and season:** summer/winter, tropical/sub-tropical
- Geological factor:** rock formation, ground water activity, geothermal resources
- Mining factor:** heat generated by oxidation of coal, heat produced by mechanical and electrical equipment due to friction and thermal dissipation (~13%); mining transport (~7%); heat produced by miners metabolism and sweating (0.4%)

10

Y. Xiaojie et al. / Mining Science and Technology (China) xxx (2011) 1-5, in press

- Central cooling
- Ice cooling
- HEMS water cooling



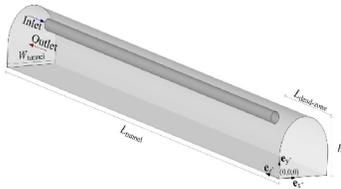
- Capture physical phenomena** in underground mines
- Develop, analyze and understand** model
- Model **verification** and experimental **validation**
- Provide link between phenomena, model, auxiliary equipments and system
- Allow for **cost effective** design, innovation and optimization at almost **less cost** and **no risk**

12



Conservation of

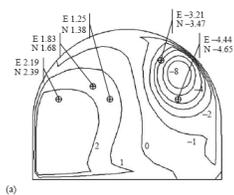
- Mass
- Momentum
- Species
- Energy
- Turbulence models
 - Spallart-Almaras
 - K-Epsilon
 - K-Omega
 - Reynolds Stress Model



- Gambit 2.3.16 for geometry design, meshing and labeling of boundaries and interior domains
- Fluent 6.3.16: finite volume solver, used defined scalars, user-defined function in C language

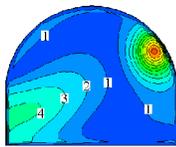
Computational cost for various turbulent models

Turbulence model	Memory (GB)	Number of iteration s	Computational time (h)
Spallart-Almaras	0.5	300	2
k-Epsilon	0.7	700	5
k-Omega	0.7	1000	8
RSM	1.0	1800	25

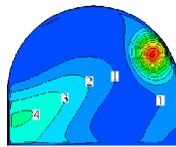


Spalart-Allmaras

K-epsilon



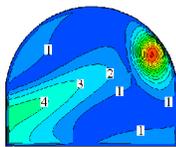
at z = 4 m from dead zone



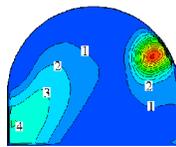
at z = 4 m from dead zone

K-omega

Reynold Stress Model



at z = 4 m from dead zone

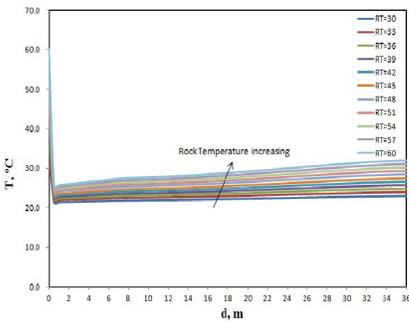


at z = 4 m from dead zone

- Spalart-Allmaras can be a desirable choice due to its low computational cost
- We are more interested to the global flow behavior rather than local eddies

Results and discussion

Effect of surrounding rock temperature



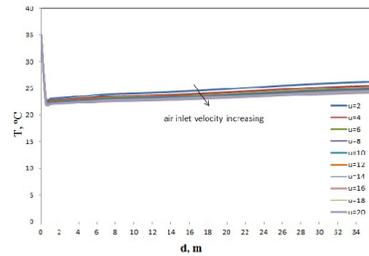
Average underground temperature along tunnel for various rock temperature; air ventilation is kept constant at 20 m/s and 20 C

- As surrounding rock temperature increases, the average underground ambient temperature rise
- This give rise to a higher probability for explosion to occur.
- Hot temperature can also cause thermal stroke to miners and reduce productivity.
- Cooling is required to reduce underground temperature

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Effect of ventilation air velocity

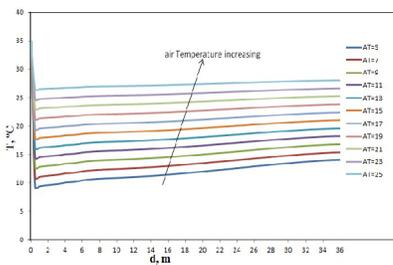


Average underground temperature along tunnel for various air ventilation velocities; rock temperature is kept constant at 30 C and ventilation air at 20 C

- Increasing ventilation air velocity can reduce underground temperature by 2 C.
- However, too high air velocity may not be comfortable for miners and dust control becomes more difficult.
- High ventilation air velocity requires high power fan which also dissipate more heat

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Effect of ventilation air temperature

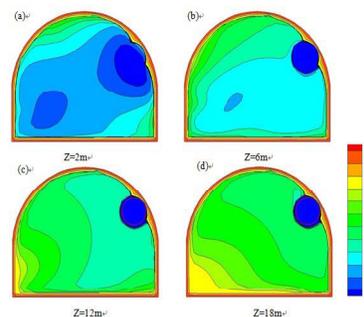


Average underground temperature along tunnel for various air ventilation temperature; rock temperature is kept constant at 30 C and ventilation air velocity at 20 m/s

- Ventilation temperature significantly affect the underground temperature.
- Underground temperature decreases as intake air temperature is reduced
- Underground temperature increases from dead-end zone (mining area) toward tunnel inlet

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Local temperature distribution inside tunnel



Local temperature distribution inside tunnel at various distance from mining zone; rock temperature 50 C; ventilation air at 20 m/s and 20 C

- Temperature inside tunnel increases as the distance from mining zone increases
- At mining zone, comfort thermal condition is achieved ($T < 30C$)
- At distance > 12 m, tunnel temperature become uncomfortable, but it is fine as no miners are working there.

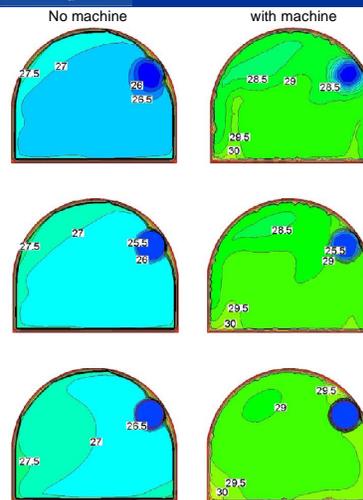
20



Typical mining machine used in room and pillar mining; the power is ~ 500kW.

Mining machine dissipate heat to underground ambient.
The mining machine is high power (~500 kW); thus relatively high amount of heat is dissipated to environment
Effect of heat generated by mining machine is investigated

21



- Mining machine give rise to underground ambient temperature increase by ~ 2 degC.
- At the base-case condition; the underground temperature is seen still at the comfort thermal condition (< 30 C)
- Mining machine needs to be taken into account when designing cooling system in underground tunnel

22

- Overview of thermal management in underground mines
- Model development
- Validation
- Effect of several operating parameters to the thermal management in underground mines: air temperature has more significant effect to control underground temperature; heat dissipation from mining machine needs to be considered when designing cooling system

23

- Include coupled temperature and humidity effect to the model.
- Model can be extended to account for spontaneous combustion with methane gas
- Include dust and water spray for dust control to the model
- Cost effective underground cooling and innovative cooling design can be proposed through modeling, and further can be tested in real mines.
- Optimization of thermal management can be investigated by combining CFD code and optimization software.

24

Modeling and Simulation of Methane Behavior in Underground Mining Face: Discrete Methane Source

Jundika C. Kurnia, Arun S. Mujumdar

Minerals, Metals and Materials Technology Centre (M3TC)
National University of Singapore

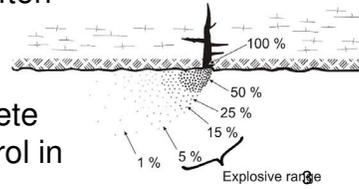
Singapore, June 6th, 2012

Outline

- Methane emission in underground mine
- Mathematical formulation
- Numerical methodology
- Results and discussion
- Summary and future directions

Methane emission in underground mine

- Methane is consistently found in underground coal reserves
- The deeper the coal, the higher the pressure and the greater amounts of methane can be found
- Methane is a significant cause of mining disasters around the globe
- Most explosions in coal mines occur when an explosive methane-air is present
- Proper handling is required to ensure safe working environment
- Methane entering a mine or tunnel often enters as a localized source at high concentration
- Here, we investigate mine with discrete methane sources and methane control in such mines



GD Taylor, JE Chilton, GVR Goodman, 2010, Guidelines for the Control and Monitoring of Methane Gas on Continuous Mining Operations, National Institute for Occupational Safety and Health.

Studied case

Methane is emitted from the discrete sources

Mine tunnel

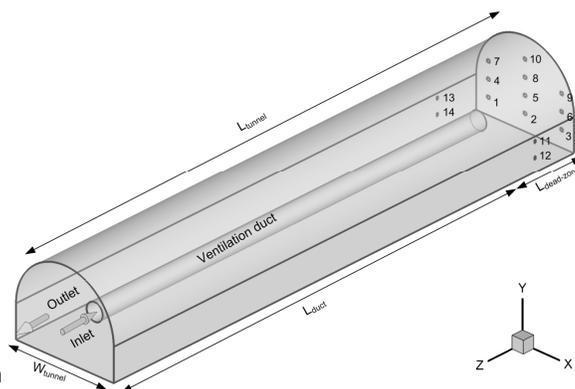
- $W_{\text{tunnel}} = 3.6 \text{ m}$
- $H_{\text{tunnel}} = 2.9 \text{ m}$
- $L_{\text{tunnel}} = 36 \text{ m}$
- $L_{\text{duct}} = 36 \text{ m}$
- $D_{\text{duct}} = 0.6 \text{ m}$
- $L_{\text{dead-zone}} = 36 \text{ m}$

Discrete sources

- Side = 0.1 m
- Horizontal spacing = 1.25 m
- Vertical spacing = 0.55 m

Ventilation duct

- Height from floor (center) = 1.9 m
- Space from the walls (center) = 0.6 m
- Diameter = 0.6 m
- Inlet velocity = 12 ms^{-1}



- Conservation of

- Mass $\nabla \cdot \rho \mathbf{U} = 0$

- Momentum $\nabla \cdot \rho \mathbf{U} \mathbf{U} = \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g}$

where

$$\boldsymbol{\sigma} = -p \mathbf{I} + [(\mu + \mu_t)(\nabla \mathbf{U} + (\nabla \mathbf{U})^T)] + \frac{2}{3} [(\mu + \mu_t)(\nabla \cdot \mathbf{U}) \mathbf{I} - \rho k \mathbf{I}]$$

- Energy $\nabla \cdot (\rho c_p \mathbf{U} T) = \nabla \cdot \left(k_{eff} + \frac{c_p \mu_t}{Pr_t} \right) \nabla T$

- Species $\nabla \cdot (\rho \omega_i \mathbf{U}) = \nabla \cdot \left(\rho D_{eff} + \frac{\mu_t}{Sc_t} \right) \nabla \omega_i$

- Mixture density $\rho = \frac{p^{ref}}{RT \sum_i \frac{\omega_i}{M_i}}$

5

- k-ε turbulence model

$$\frac{\partial k}{\partial t} + \nabla \cdot (\rho \mathbf{u} k) = \nabla \cdot \left[\left(\mu + \frac{\rho \mu_t}{\sigma_k} \right) \nabla k \right] + \rho \mu_t G - \rho \varepsilon,$$

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\rho \mathbf{u} \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\rho \mu_t}{\sigma_k} \right) \nabla \varepsilon \right] + \frac{C_{1\varepsilon} \rho \mu_t G \varepsilon}{k} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k},$$

$$G = 2 \left(\left[\frac{\partial u}{\partial x} \right]^2 + \left[\frac{\partial v}{\partial y} \right]^2 + \left[\frac{\partial w}{\partial z} \right]^2 \right) + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2,$$

$$\mu_t = C_\mu \frac{k^2}{\varepsilon},$$

Nomenclature:

u, v, w = component velocity
 μ_t = turbulent viscosity
 k = turbulent kinetic energy
 ε = turbulent dissipation
 G = turbulent generation rate

$C_{1\varepsilon} = 1.44$
 $C_{2\varepsilon} = 1.92$
 $C_\mu = 0.09$
 $\sigma_k = 1.0$
 $\sigma_\varepsilon = 1.0$

6

- **Gambit**: creating geometry, meshing, labeling boundary condition
- **Fluent**: solving for conservation of mass, momentum, turbulence and energy
- **Discrete phase models (DPM)**: to capture dust emission and movement
- Finer mesh in the boundary layer zone, and increasingly coarser; mesh independence test $\sim 1.000.000$ cells.
- Relative residual 10^{-6} for all dependent variable.
- It took around 6-8 h to converge in Six-Core 3.2 GHz with 96 GB RAM.

7

Part 1

DISCRETE METHANE SOURCE

- Constant methane emission ($0.05 \text{ m}^3 \text{ s}^{-1}$)
- Constant methane source inlet velocity (0.5 m s^{-1})

8

Constant methane emission



Operating parameters of studied cases

Studied Cases	Sources														V _{CH4} (ms ⁻¹)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Case 1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	0.36
Case 2	√	√	√	√	√	√	√	√	√	√					0.50
Case 3											√	√	√	√	1.25
Case 4	√	√	√	√	√	√	√	√	√	√	√	√			0.42
Case 5	√	√	√	√	√	√	√	√	√	√			√	√	0.42
Case 6		√		√	√	√		√		√					0.83
Case 7	√		√				√		√						1.25
Case 8		√								√					2.5

√ indicates sources emitting methane

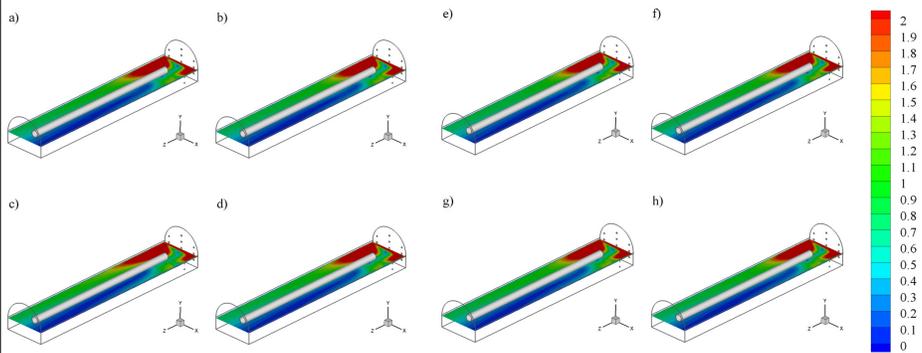
Methane emission was kept constant at 0.05 m³ s⁻¹ (Torano et al., 2009). We will study the effect of methane emission origin on the methane dispersion in the mining tunnel.

J. Torano, S. Torno, M. Menendez, M. Gent, J. Velasco, Models of methane behaviour in auxiliary ventilation of underground coal mining, International Journal of Coal Geology 80 (2009) 35-43

Constant methane emission



Velocity contour

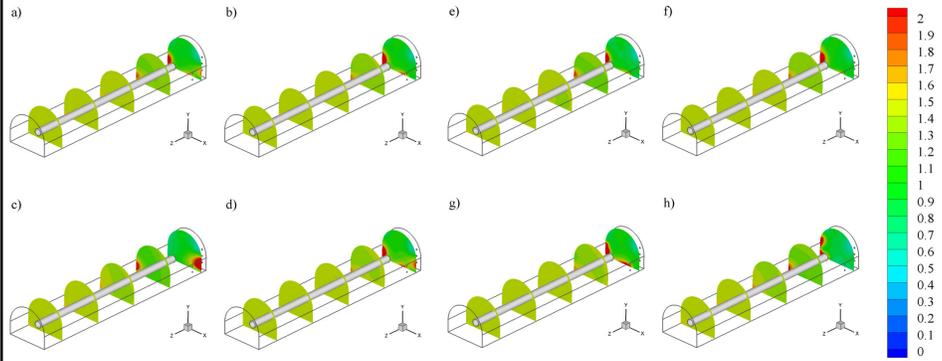


Velocity contour (m s⁻¹) at height 0.6 m at height 1 m from the floor

- The influence of discrete source on the ventilation airflow in the channel is negligible
- Mine tunnel:
 - W_{tunnel} = 3.6 m
 - H_{tunnel} = 2.9 m
 - L_{tunnel} = 36 m
- Discrete sources:
 - L_{duct} = 36 m
 - D_{duct} = 0.6 m
 - L_{dead-zone} = 36 m
 - Side = 0.1 m
 - Horizontal spacing = 1.25 m
 - Vertical spacing = 0.55 m

Constant methane emission

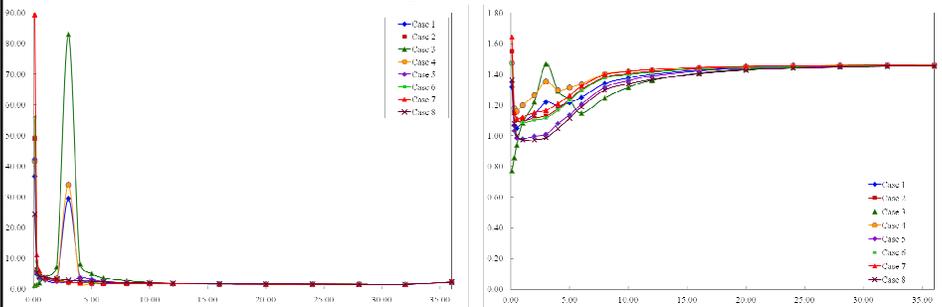
Methane concentration



- Methane distribution in the mine tunnel is considerably affected by variation of sources from which methane is emitted
- At location far from the mining face, methane concentration is relatively uniform and the influence of different sources is negligible

Constant methane emission

Methane concentration along mine tunnel



Maximum methane concentration (% v/v) along the tunnel

Crosssection average methane concentration (% v/v) along the tunnel

- Variation of discrete sources at which methane is released affect methane distribution in the front section of the mine tunnel (area near mining face)
- Overall, methane concentration on the front section of the tunnel mine is higher when all sources release methane (note that the amount of methane released is kept constant at $0.05 \text{ m}^3 \text{ s}^{-1}$).
- At location far from the mining face (after 25 m from the face) methane concentration for all configuration is relatively similar

Constant methane inlet velocity



Operating parameters of studied cases

Studied Cases	Sources														V _{CH4} (ms ⁻¹)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Case 1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	0.50
Case 2	√	√	√	√	√	√	√	√	√	√					0.50
Case 3											√	√	√	√	0.50
Case 4	√	√	√	√	√	√	√	√	√	√	√	√			0.50
Case 5	√	√	√	√	√	√	√	√	√	√			√	√	0.50
Case 6		√		√	√	√		√		√					0.50
Case 7	√		√				√		√						0.50
Case 8		√								√					0.50

√ indicates sources emitting methane

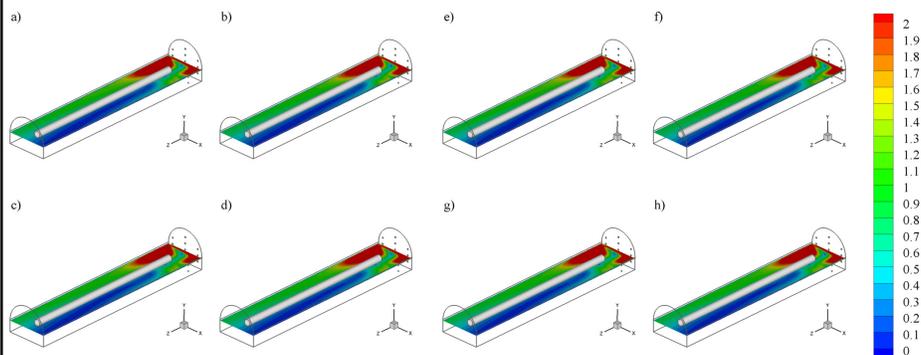
Methane source inlet velocity is kept constant at 0.50 m s⁻¹. We will study the effect of origin and amount of methane emitted to the tunnel on the methane dispersion in the mining tunnel.

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Constant methane inlet velocity



Velocity contour



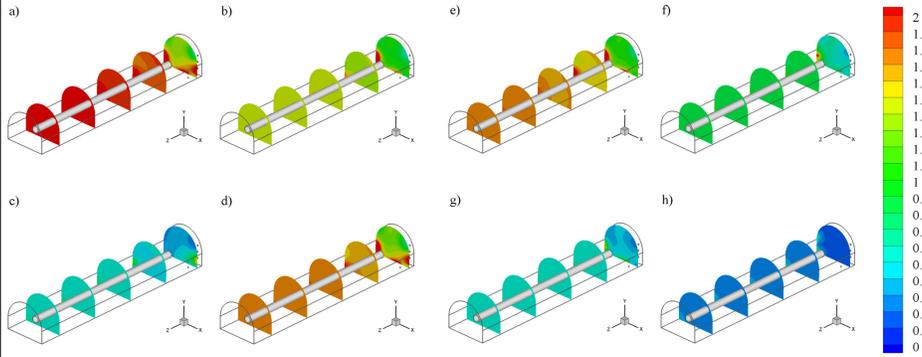
Velocity contour (m s⁻¹) at height 0.6 m at height 1 m from the floor

- Similar with constant emission cases, the influence of different discrete source on the ventilation airflow in the channel is negligible
- Mine tunnel:
 - W_{tunnel} = 3.6 m
 - H_{tunnel} = 2.9 m
 - L_{tunnel} = 36 m
- Discrete sources:
 - L_{duct} = 36 m
 - D_{duct} = 0.6 m
 - L_{dead-zone} = 36 m
 - Side = 0.1 m
 - Horizontal spacing = 1.25 m
 - Vertical spacing = 0.55 m

14

Methane concentration

Methane concentration

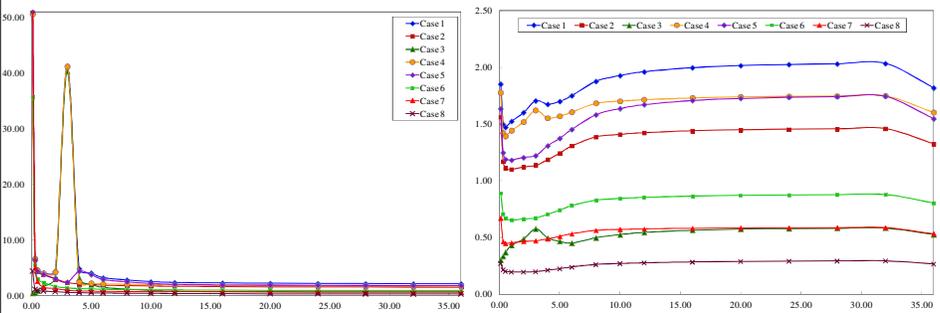


Methane concentration (% v/v) at 1, 8, 16, 24, 32 m from the mining face

- Methane distribution in the mine tunnel is significantly affected by variation of sources from which methane is emitted.
- Since all sources emitted methane at same velocity, more sources result in higher concentration in the mine tunnel.
- Similar to the constant emission case, at location far from the mining face, methane concentration is relatively uniform

Maximum methane concentration

Methane concentration along mine tunnel



Maximum methane concentration (% v/v) along the tunnel

Crosssection average methane concentration (% v/v) along the tunnel

- Variation of discrete sources at which methane is released affect methane significantly affected methane distribution along the mine tunnel.
- More discrete sources release methane lead in higher methane concentration in the mine tunnel.
- It highlights the importance of methane monitoring to detect at which location methane source exist so that proper methane handling can be carried out.

Part 2

METHANE HANDLING

- Various duct placement
- Application of baffle to direct the flow

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Various duct placement

Schematics of the studied cases

Mine tunnel

- $W_{\text{tunnel}} = 3.6 \text{ m}$
- $H_{\text{tunnel}} = 2.9 \text{ m}$
- $L_{\text{tunnel}} = 36 \text{ m}$
- $L_{\text{duct}} = 36 \text{ m}$
- $D_{\text{duct}} = 0.6 \text{ m}$
- $L_{\text{dead-zone}} = 36 \text{ m}$

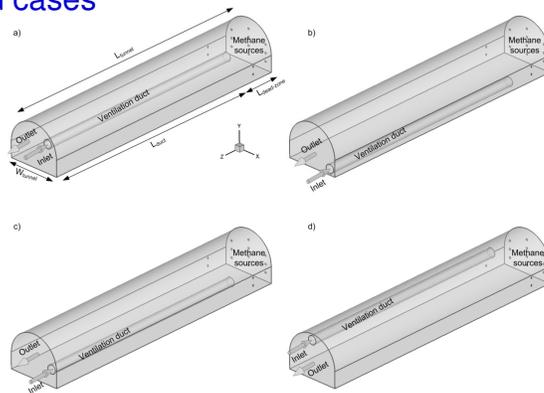
Discrete sources

- Side = 0.1 m
- Horizontal spacing = 1.25 m
- Vertical spacing = 0.55 m

Ventilation duct

- Diameter = 0.6 m

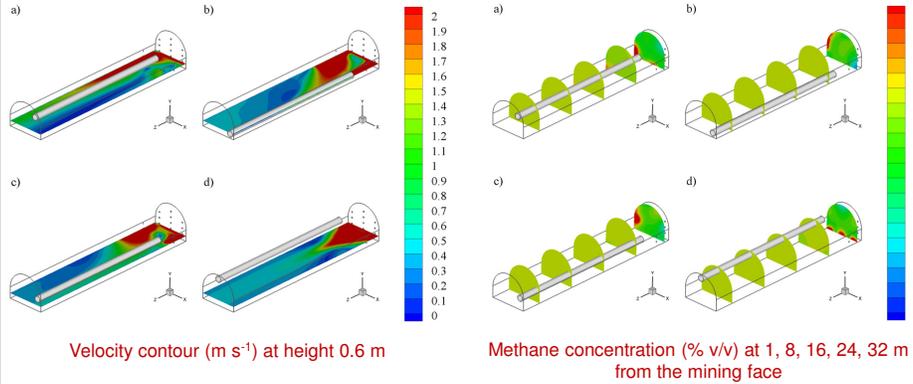
Duct placement:	Case 1	Case 2	Case 3	Case 4
(duct center)	(Base)	(Bottom)	(Side)	(Top)
Height (m)	1.9	0.7	1.1	2.5
Space from wall (m)	0.6	0.4	0.4	1.8



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Various duct placement

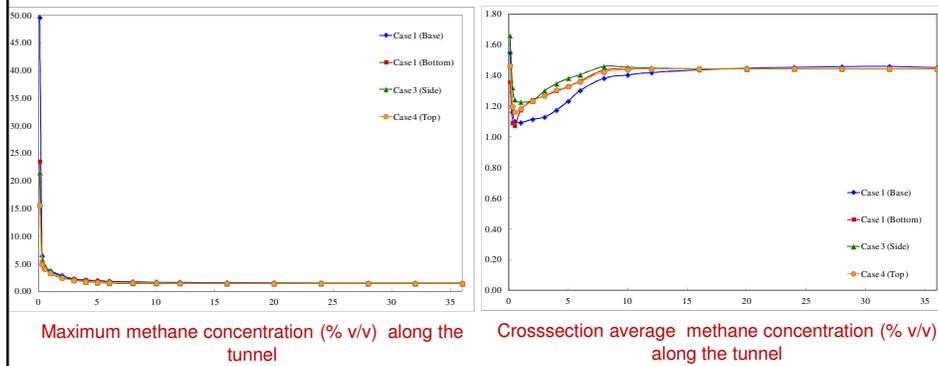
Velocity and methane contour



- Variation in duct placement significantly affect airflow profile in the mine tunnel and in turn methane dispersion in the tunnel.
- The influence of this variation is more prominent on the front section of the mine tunnel where methane distribution is directly affected by the airflow from the ventilation duct

Various duct placement

Methane concentration along mine tunnel



- Base configuration, where ventilation duct located on the top right of the tunnel, performs best in handling methane emission.
- All methods could maintain methane level below the explosion limit (5% methane concentration)
- To reduce energy, intermittent flow (where ventilation flow operate between half and full power) will be introduced and investigated
- In the next study, we will investigate effectiveness of baffle to direct the ventilation air flow²⁰

Application of baffle

Schematics of the studied cases

Mine tunnel

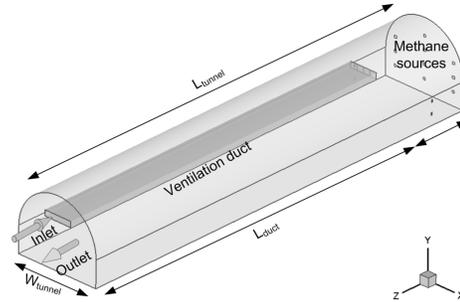
- $W_{\text{tunnel}} = 3.6 \text{ m}$
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- $L_{\text{tunnel}} = 36 \text{ m}$
- $L_{\text{duct}} = 36 \text{ m}$
- $D_{\text{duct}} = 0.6 \text{ m}$
- $L_{\text{dead-zone}} = 36 \text{ m}$

Discrete sources

- Side = 0.1 m
- Horizontal spacing = 1.25 m
- Vertical spacing = 0.55 m

Ventilation duct

- Height from floor (center) = 1.9 m
- Width = 1.2 m (divided into 4 section)
- Height = 0.24 m
- Inlet velocity = 12 ms^{-1}

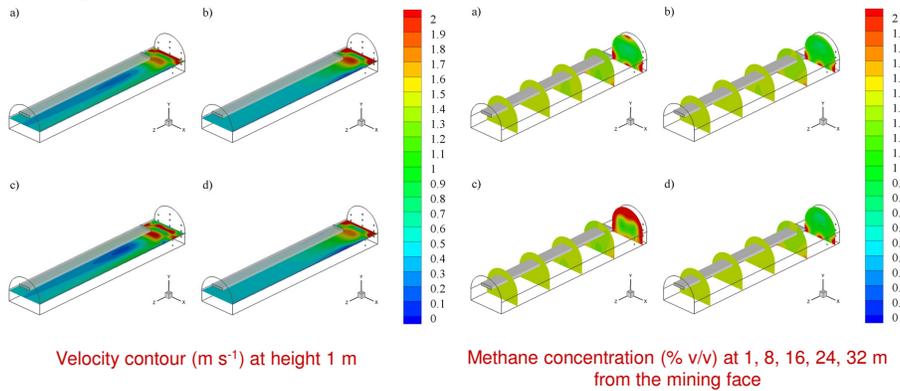


- Case 1 = normal flow, all section 11.8 m s^{-1}
- Case 2 = normal flow, 2 section in the center 15.74 m s^{-1} , 2 side section 7.87 m s^{-1}
- Case 3 = normal flow, 2 section in the center 7.87 m s^{-1} , 2 side section 15.74 m s^{-1}
- Case 4 = flow directed to the center, all section 11.8 m s^{-1}

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Application of baffle

Velocity and methane contour



Velocity contour (m s^{-1}) at height 1 m

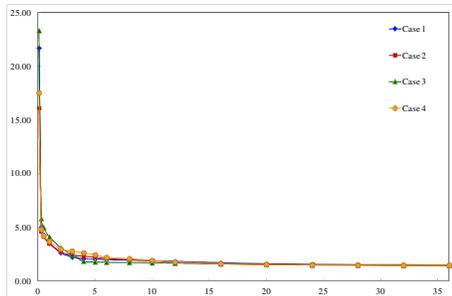
Methane concentration (% v/v) at 1, 8, 16, 24, 32 m from the mining face

- Application of baffle significantly affect airflow profile in the mine tunnel and in turn methane dispersion in the tunnel.
- The influence of this variation is more prominent on the front section of the mine tunnel where methane distribution is directly affected by the airflow from the ventilation duct

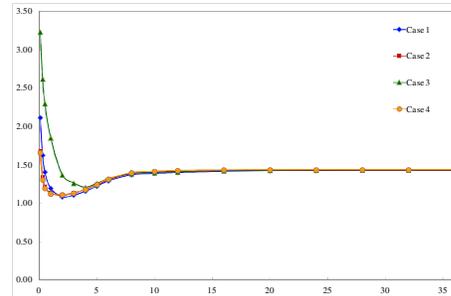
22

Maximum methane concentration

Methane concentration along mine tunnel



Maximum methane concentration (% v/v) along the tunnel



Crosssection average methane concentration (% v/v) along the tunnel

- Case 2,3 and 4 has comparable performance in reducing methane concentration on the mining face. These indicate that focusing ventilation flow into a point is more effective as compared to dispersed it on several point
- All methods could maintain methane level below the explosion limit (5% methane concentration)
- More studies and investigation is needed to obtain optimum ventilation duct design and operating parameters (number of baffle, velocity for each baffle, direction of ventilation airflow from the baffle)

Summary

- Mathematical model for methane emission and dispersion is developed
- Variation on discrete methane sources has been investigated
- Results on discrete methane sources indicates that different number of methane sources may need different handling to reduce methane concentration in the mine tunnel
- Effect of duct placement and application of baffle to direct the flow has been studied
- Base-case where ventilation duct located at the top right of the tunnel offers better methane handling compare to other methods.
- Next study will investigate implementation of intermittent ventilation airflow to reduce energy usage.

Minerals, Metals and Materials Technology Centre (M3TC)

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Modeling and Simulation of Dust Behavior in Underground Mining Face

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Singapore, June 6th, 2012

Outline

- Dust emission in underground mine
- Mathematical formulation
- Numerical methodology
- Results and discussion
- Summary and future directions

Dust emission in underground mine



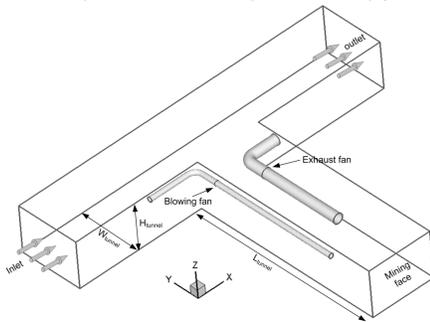
- Dust in underground mine seriously endangers safe production and miner's health.
- Major source of dust is the mining face where the coal is extracted.
- The airflow directly influence dust distribution in the mining face
- Proper control and management are required to ensure safe working environment
- Here various methodology are investigated:
 - Application of blowing and exhaust fan
 - Implementation of brattice to direct the flow to the mining face
 - Combination of those technique

3

Studied case



Dust is generated during the mining process at the mining face

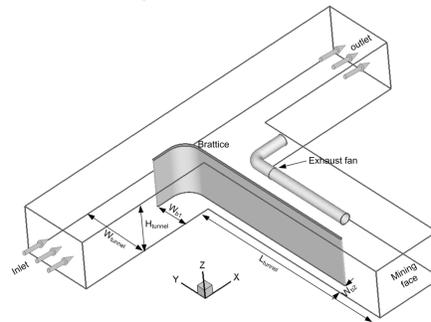


Mine tunnel

- $W_{\text{tunnel}} = 4 \text{ m}$
- $H_{\text{tunnel}} = 2.9 \text{ m}$
- $L_{\text{tunnel}} = 12 \text{ m}$

Blowing fan

- Diameter = 0.3 m
- Height from floor (center) = 2 m
- Space from the walls (center) = 0.25 m
- Setback from mining face = 3 m



Exhaust fan

- Diameter = 0.6 m
- Height from floor (center) = 0.65 m
- Space from the walls (center) = 0.6 m
- Setback from mining face = 6 m

Brattice

- $W_{b1} = 2 \text{ m}$
- $W_{b2} = 0.5 \text{ m}$

Inlet velocity = 2 ms^{-1}

4

- Conservation of

- Mass $\nabla \cdot \rho \mathbf{U} = 0$

- Momentum $\nabla \cdot \rho \mathbf{U} \mathbf{U} = \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g}$

where

$$\boldsymbol{\sigma} = -p \mathbf{I} + [(\mu + \mu_t)(\nabla \mathbf{U} + (\nabla \mathbf{U})^T)] + \frac{2}{3} [(\mu + \mu_t)(\nabla \cdot \mathbf{U}) \mathbf{I} - \rho k \mathbf{I}]$$

- Fan law

$$\Delta p_{\text{fan}} = \mathfrak{C}_1 (u_{\text{fan}})^2 + \mathfrak{C}_2 u_{\text{fan}} + \mathfrak{C}_3$$

- Discrete phase modeling

$$\frac{du_p}{dt} = F_D (u - u_p) + \frac{g_x (\rho_p - \rho)}{\rho_p} + F_x$$

where

$$\mathfrak{C}_1 = -13.5 \text{ Pa s}^2 \text{ m}^{-2}$$

$$\mathfrak{C}_2 = 352.6 \text{ Pa s m}^{-1}$$

$$\mathfrak{C}_3 = -629.9 \text{ Pa}$$

$$F_D = \frac{18\mu C_D \text{Re}}{\rho_p d_p^2 24}, C_D = f(\text{Re}_p)$$

$$\text{Re} \equiv \frac{\rho d_p |u_p - u|}{\mu}$$

5

- k-ε turbulence model

$$\frac{\partial k}{\partial t} + \nabla \cdot (\rho \mathbf{u} k) = \nabla \cdot \left[\left(\mu + \frac{\rho \mu_t}{\sigma_k} \right) \nabla k \right] + \rho \mu_t G - \rho \varepsilon,$$

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\rho \mathbf{u} \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\rho \mu_t}{\sigma_k} \right) \nabla \varepsilon \right] + \frac{C_{1\varepsilon} \rho \mu_t G \varepsilon}{k} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k},$$

$$G = 2 \left(\left[\frac{\partial u}{\partial x} \right]^2 + \left[\frac{\partial v}{\partial y} \right]^2 + \left[\frac{\partial w}{\partial z} \right]^2 \right) + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right)^2,$$

$$\mu_t = C_\mu \frac{k^2}{\varepsilon},$$

Nomenclature:

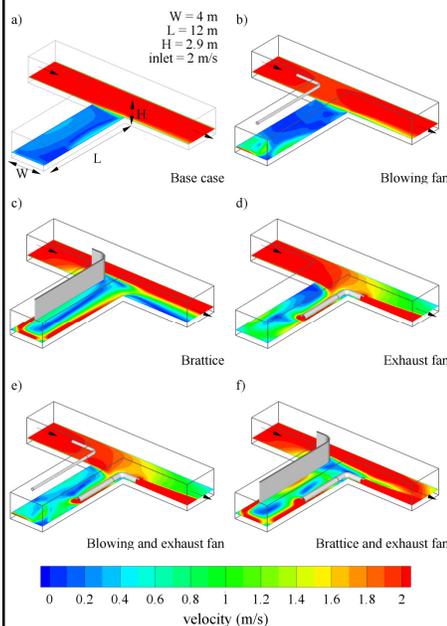
u, v, w = component velocity
 μ_t = turbulent viscosity
 k = turbulent kinetic energy
 ε = turbulent dissipation
 G = turbulent generation rate

$C_{1\varepsilon} = 1.44$
 $C_{2\varepsilon} = 1.92$
 $C_\mu = 0.09$
 $\sigma_k = 1.0$
 $\sigma_\varepsilon = 1.0$

6

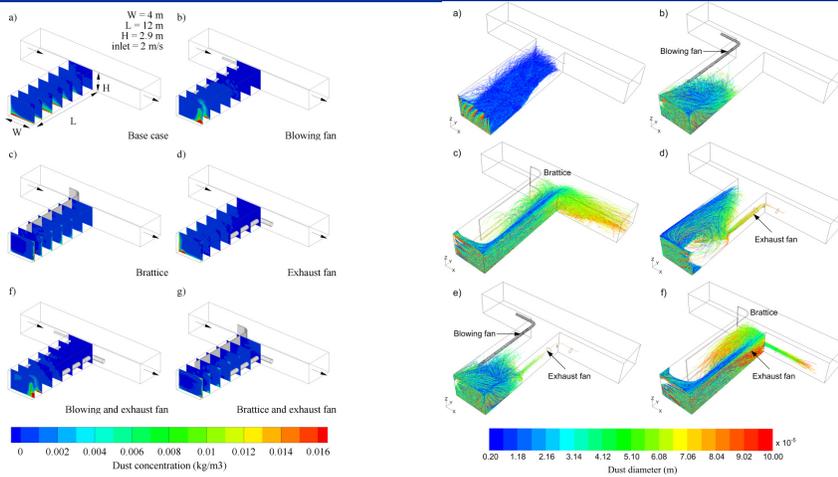
- **Gambit**: creating geometry, meshing, labeling boundary condition
- **Fluent**: solving for conservation of mass, momentum, turbulence and energy
- **Discrete phase models (DPM)**: to capture dust emission and movement
- Finer mesh in the boundary layer zone, and increasingly coarser; mesh independence test ~ 1.000.000 cells.
- Relative residual 10^{-6} for all dependent variable.
- It took around 6-8 h to converge in Six-Core 3.2 GHz with 96 GB RAM.

Velocity contour



- For base case, a very low air velocity observed in the mining area
- Blowing fan provide airflow only on the mining face
- Exhaust fan pulls out fresh air instead air from mining face
- Brattice provide sufficient ventilation air on the mining face

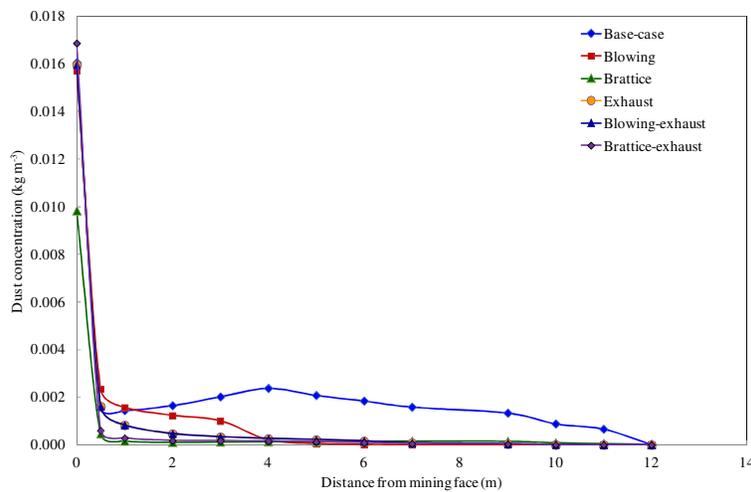
Dust emission and dispersion



- Without additional ventilation, dust is accumulated in the mining area and could endanger miner's health.
- Blowing fan push the dust to the front section. I could not mitigate the dust away from the mining area.
- Brattice perform best by evacuating the dust from the mining area.

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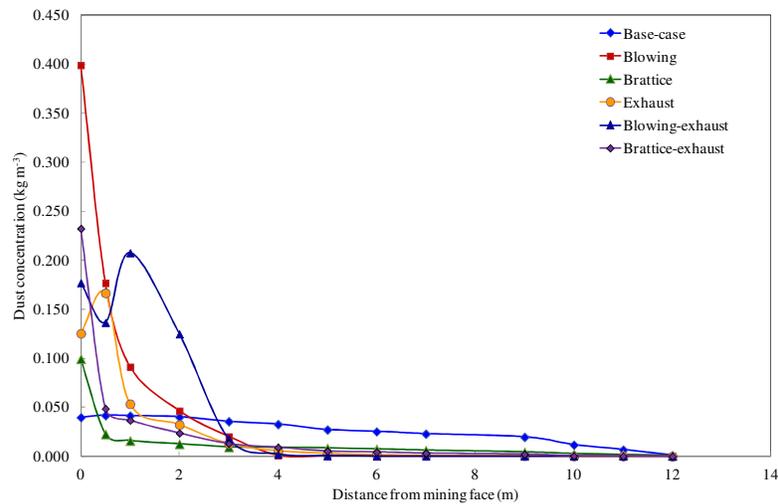
Average dust concentration



- Without additional ventilation, dust concentration is high and distributed evenly in the mining area.
- Brattice offers best dust control in the mining area

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Maximum dust concentration



- All additional ventilation push the dust to the front section of mining area, mirrored by high dust concentration in the first few meter from the mining face
- Applying additional ventilation reduce dust concentration in the mining area 11
- Brattice maintain dust concentration at minimum level

Summary

- Mathematical model for dust emission and dispersion is developed
- Various methods of dust mitigation have been investigated
- Implementation of brattice to direct the flow to the mining face is the most effective. However, it may restrict movement of mine operator and vehicle.
- Utilization of air curtain to replace physical brattice.

Content

- Innovative Idea(s) for dust control in mine ventilation
- Preliminary CFD simulation with dust particles dispersion

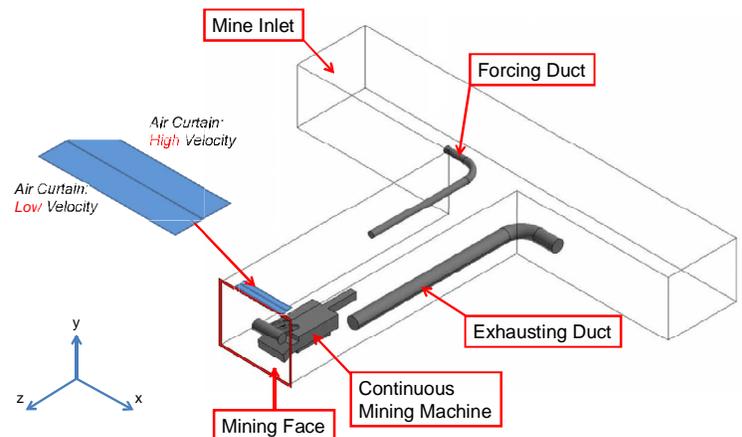
Dust control in mine ventilation

Ms. Tan Hwee Sien
Dr. POH Hee Joo
Prof. Arun Mujumdar
3 Aug 2012

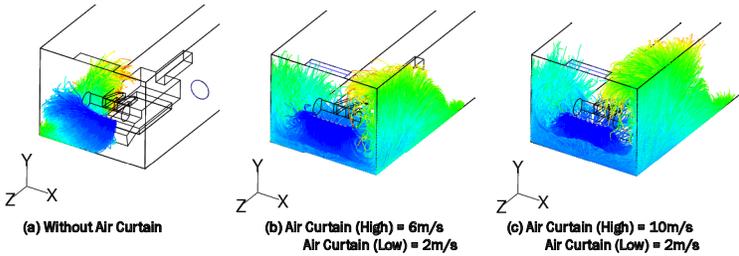
Innovative Idea(s) for dust control in mine ventilation

- **Cascading air curtain system** with lower velocity near dust source (prevent mixing of dust with surrounding) and higher velocity away from dust source (higher penetration and vertical momentum downwards)
- High pressure, water fog spray as potential dust control system in mining environment
- Top Push- Bottom Pull local ventilation for effective dust control
- Electro-static dust control device

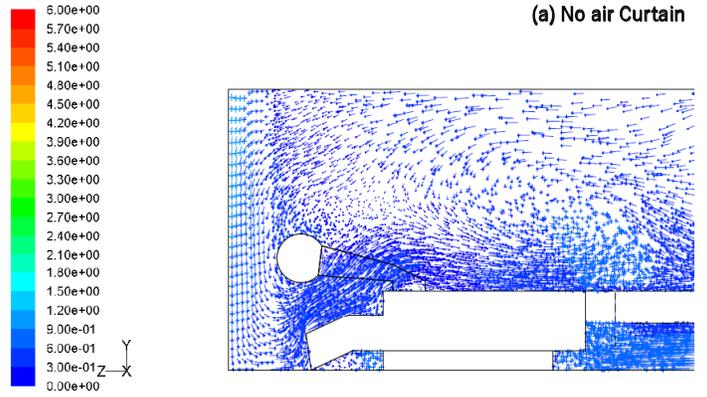
Geometrical Model – Isometric View



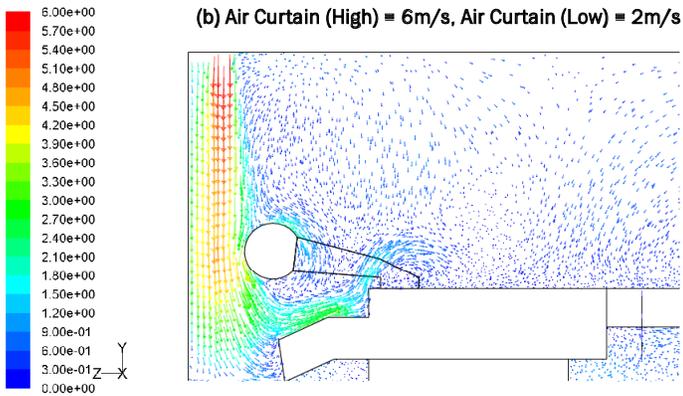
Particle Track of Dust Distribution



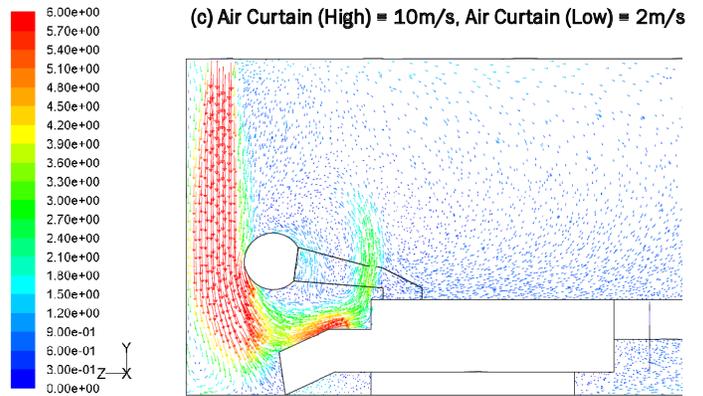
Velocity Vector Plot of Cut-plane x=0m, near the Mining Face



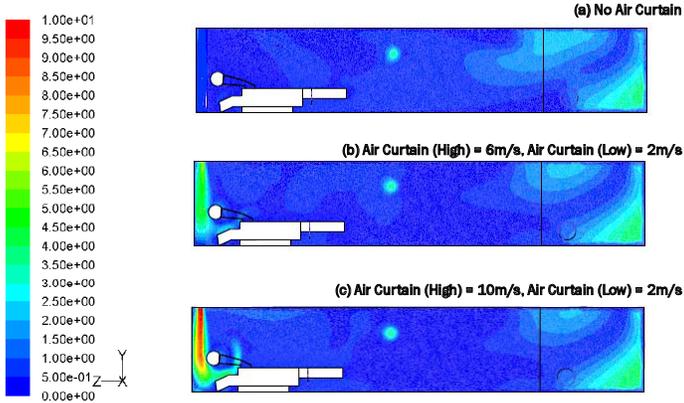
Velocity Vector Plot of Cut-plane x=0m, near the Mining Face



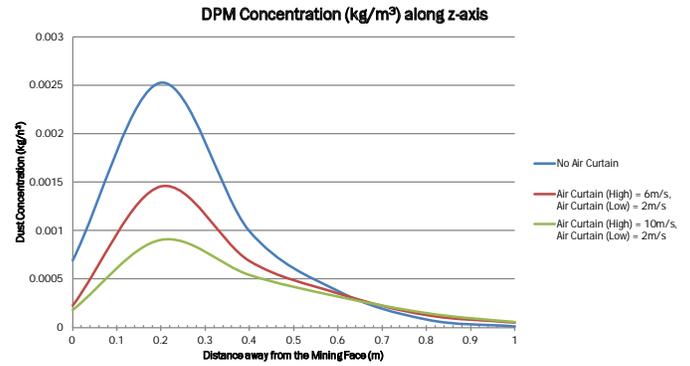
Velocity Vector Plot of Cut-plane x=0m, near the Mining Face



Velocity Contour Plot of Cut-plane $x=0m$



Dust Concentration near the Mining Face



Summary

- Use of cascading air curtain with
 - Lower velocity near to mining face
 - Higher velocity at the controlled environment at the mining tunnel
- provides good means of containing dust at the mining region, as well as establishing good dust sealing effect to the mining tunnel
- Further exploratory study with water droplet coupling with cascading air curtain effect is being investigated