Fog control and prevention in underground mine travelways using refrigeration

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ABSTRACT

Fog formation in underground mines can cause poor visibility in travel ways, accelerate corrosion of ground support and steel infrastructure, and damage electrical and electronic devices continually exposed to moisture. Fog in mines is usually formed from the adiabatic decompression and cooling of humid air as it ascends, causing water vapour to condense into suspended fine water droplets.

Warm climate mines typically exhaust through dedicated shafts largely negating the hazardous potential of fog, however, cooler climate mines often exhaust warm humid air through travelways to minimise heating requirements and prevent freezing in main travelways during winter periods. Hazards resulting from poor visibility due to fog are typically addressed through reduced traffic speed, guide lights and traffic control procedures, which only partially reduce the risks, and result in reduced productivity and increased operating costs.

Fog can normally only be reduced or eliminated by heating or dehumidifying air, or by the physical removal of water droplets from air. Dehumidification is a common industrial process used in HVAC systems to control air quality and comfort but has yet to be routinely used at an industrial scale in underground mines. This paper describes a process of using refrigeration technology to create a dehumidification process to control large volumes of fog. The process is modelled in Ventsim™ version 6.0 (by Howden Ventsim, Howden) to demonstrate the theoretical effectiveness, efficiency, and cost of a refrigerative dehumidification system compared to an equivalent electric heat system and discusses practical ways to implement the technology in typical underground mines.

INTRODUCTION

Fog is the presence of fine suspended water droplets in the air and is part of a wider psychrometric process related to the behaviour of mixed air and water vapour under differing temperatures and pressures. The definition of fog is internationally recognised by the Federal Coordinator for Meteorology (2005) as the presence of fine water droplets that reduce visibility to less than 1000 m. Assuming fine droplets, this equates to an initial water concentration for light fog of between 50–100 mg/m^3 of air, increasing to over 1000 mg/m^3 for thick fog. This is a simplification, as visibility through fog is also associated with the water droplet size, with finer droplets reducing visibility for the same mass density. If saturated air approaches its dew point temperature, excess water condensates to form suspended liquid water droplets (often assisted by existing nuclei of diesel particulates or dust).

Fog is recognised as a working hazard in mines, particularly in cold climate regions where the exhaust air is often directed through main travelways to reduce heating requirements and eliminate icing hazards (Figure 1). Poor visibility causes hazards for traffic interactions, productivity can suffer due to reduced travel speeds, moisture accelerates the corrosion of steel and ground support, and water can ingress into electrical infrastructure.

There is little research on reducing fog in underground mines. Traditional methods of controlling fog hazards include tolerating the problem through traffic control, procedures, speed restrictions and guide lights, or sometimes in exceptional circumstances closing sections of the mine where fog has become unmanageable.

FIG 1 – Access portal fog emissions traffic control.

FOG REMOVAL METHODS

Fog can be removed via many methods, several of which are described below:

- Agitating air with increased flow and turbulence.
- Mixing with dryer air sources.
- Physical removal of liquid moisture droplets from the air.
- Removal of water vapour (latent heat) from the air.
- Heating the air to increase the water vapour carrying capacity.

Agitation

Schimmelpfennig (1982) researched numerous methods of fog reduction including heating the mine air, chemically drying moist air, refrigeration of air, use of centrifugal fan scrubbers, chilling intake air and increasing airflow using additional fans. Schimmelpfennig suggested the most plausible solution was to increase air velocity to promote air mass mixing and evaporation. Centrifugal fan scrubbers and mist eliminators provided an effective mechanical means of removing water droplets. Coupled with the added fan power and heat generated in the process, the study found the fog could effectively be removed, but at a relatively high capital and operating cost.

Water droplet removal

Martikainen (2007) discusses the analysis of fog in three sub-artic mines in Finland; Pyhäsalmi Mine, Orivesi Mine, and Louhi Mine including the causes and potential for removal or reduction of the fog. Mechanical methods using filters or screens to capture droplets were trialled but found to have only limited success in local fog removal. An aluminium net and a mist eliminator and fibrous filter fabric combination provided the best results but still failed to completely eliminate the fog.

The effectiveness of both agitation and water droplet removal in a mine ramp application is questionable as the methods must capture all airflow and remove no latent heat. In an upcasting ramp system, the fog quickly re-forms once the air further reduces in density and cools.

Heating

Direct electric heating is occasionally used in foggy mines, and Martikainen (2006) notes heating with fans and electric heaters reduces fog by raising the temperature and increasing the moisture-carrying capacity of air while evaporating any existing moisture droplets. Temporary fog-reducing benefits can be seen practically in circumstances such as the operation of large diesel trucks, large fans or waste heat from infrastructure such as compressor stations or transformer stations.

Heating of air however does not remove moisture, and some processes such as diesel equipment can add more moisture through exhaust gases to the air. Heating also tends to be energy inefficient as any rise in temperature potentially causes more rapid heat loss to surrounding rock strata. Ultimately, the fog reforms once the air approaches the dew point temperature again.

Water vapour removal

Any fog elimination process that relies only on liquid water droplet removal, or heats the air without removing moisture, risks having only short-term benefits in an upcast ramp system. Efficient, long-lasting fog elimination requires the removal of water vapour (latent heat) to ensure the psychrometric properties of the air are altered to allow re-cooling without immediate fog formation.

Latent heat removal reduces the specific moisture content (water mass) in the air rather than only reducing relative humidity (% of water vapour carrying capacity). The 'drying' of the air allows any remaining water droplets (fog) to be re-evaporated into the air if not removed. If enough latent heat moisture is removed, it provides a buffer to allow further moisture addition or cooling without fog re-formation. There are two main methods of latent heat removal: desiccant (or absorption) dehumidification, and condensate (or refrigerative) dehumidification.

The first commercial dehumidifier was developed by William Carrier in 1902 (Teitelbaum, Miller and Meggers, 2023) using refrigeration technology and his work led to the understanding of dew-point behaviour and the development of the psychrometric chart in 1911 (Simha, 2012). Carrier (among others before) realised the importance of moisture control in industry and his work sparked a technological revolution in the science of conditioning air and the modernisation of HVAC processes (heating, ventilation, and air conditioning).

Desiccant dehumidification

Desiccant dehumidification requires a moisture-absorbing hydrophilic material such as silica gel to remove water vapour from the air (Figure 2). Moist air passed through the dry (activated) gel is dried, passing moisture to the gel. The saturated gel can then be heated to remove absorbed water, thereby reactivating it for reuse in the process. The method is commonly used in industrial HVAC and dryers to reduce humidity and has the advantage of simplicity and the ability to work in cold temperatures (less than 10°C). The disadvantages are the high relative power cost and the logistics of removing moisture from the desiccant without it re-entering the airflow. If this process was used underground, the humid air from the desiccant regeneration would need to be rejected into an exhaust system to prevent it from re-entering the mine access and causing more fog when cooled.

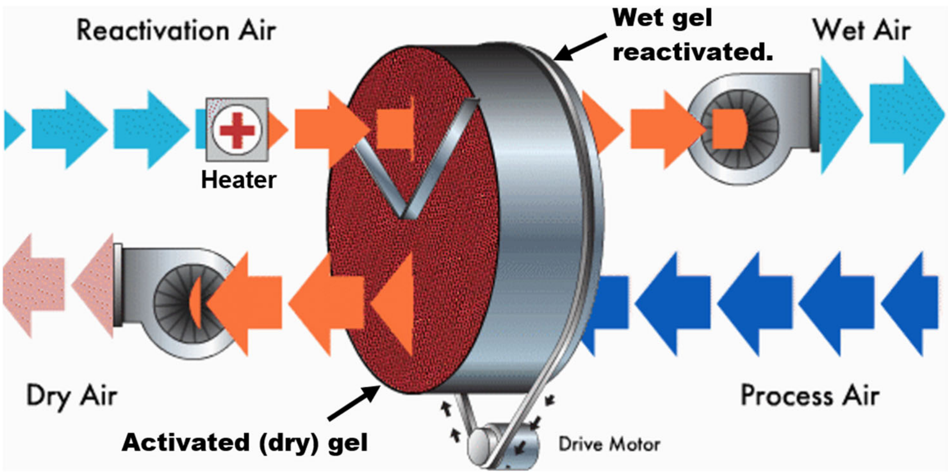

FIG 2 – Example of rotor desiccant dehumidification (Munters, 2024).

Refrigerative dehumidification

Refrigeration dehumidification uses a refrigeration process to chill air to below the dew point temperature, forcing condensate water to be extracted and disposed of in a liquid state as shown in Figure 3. The combination of chilled air, condenser heat rejection and mechanical heat of the refrigeration process is re-added as a mix of warmer dryer air to the more humid surroundings, reducing both relative humidity and specific moisture.

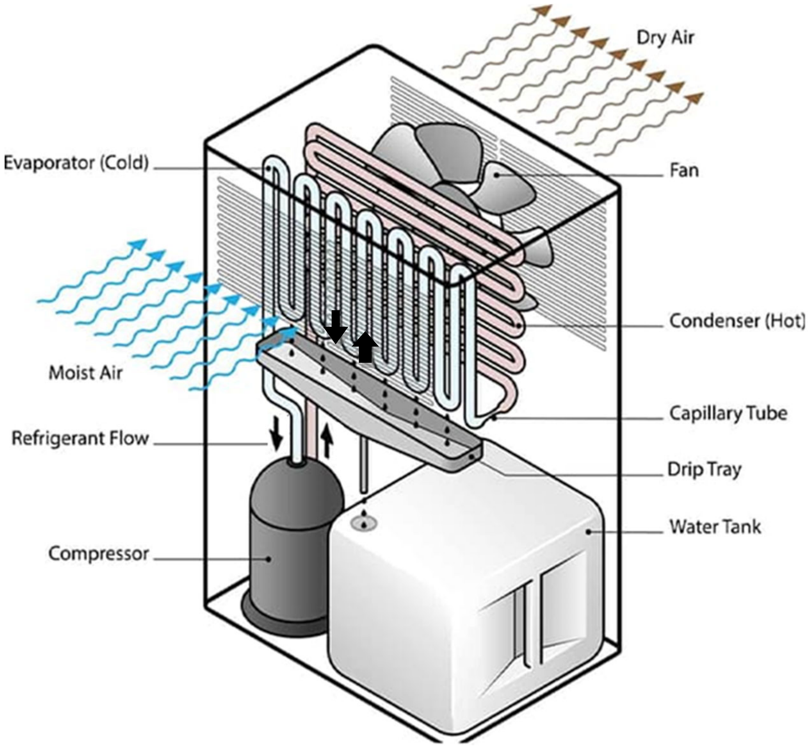

FIG 3 – Example of refrigerative dehumidification (Alorair, 2024).

The method is also commonly used in HVAC processes and has the advantage of higher energy efficiency, but with the disadvantages of greater mechanical complexity, and poorer efficiency in cooler temperatures (under 10°C) due to the limits imposed by evaporator plate icing and reduced heat transfer efficiency.

Mine fog removal with refrigeration

Refrigeration has been successfully used for many decades for cooling in hot underground mines and applied in processes such as bulk air cooling, spot cooling, chilled water and ice manufacture. Refrigerative dehumidification likewise has a long history of successful use in industrial HVAC, business, and residential applications. The application of dehumidification strategies in underground environments to reduce fog is therefore not considered theoretical or speculative as this paper simply researches and models new applications of proven processes.

Mine refrigerative dehumidification

The dehumidification process proposed for mine fog removal is similar to mine refrigerative spot cooling with a few minor changes. The plant is located underground in or near the foggy region, treats a portion of the passing foggy airflow and allows the treated and untreated streams to mix downstream in the normal flow direction. The process should not be disruptive to traffic and can be scaled to fit available infrastructure or excavations accordingly.

A spot-cooling refrigeration plant typically contains two main components: a compressor chiller circuit and a cooling circuit. The compressor pumps refrigerant gas through condenser heat exchanger coils at high pressure which condenses the gas to a liquid, releasing heat. The heat is removed from the coils with air or water. The compressed liquid refrigerant is then piped and evaporated through cooling coils, absorbing heat and chilling any air or water passing around the coils. The chilled air or water is used to cool a portion of the mine air, while the heat rejected from the compressor condenser circuit is sent to the air exhaust or a hot water reject circuit.

A refrigerative dehumidification process uses the same equipment but applies several configuration changes:

- The refrigerant condenser heat exchanger returns heat to the main air circuit instead of discarding it to exhaust. The heat increases the air temperature, decreasing relative humidity and helping reduce or eliminate fog.
- The chilled air produced from the evaporator cooling coils (minus any condensate water that is captured and removed) is used to assist the condenser heat exchanger in removing heat, increasing the efficiency of the refrigerant condensation process.
- Only a portion of the passing air is treated. The 'treated air' that has passed through the cooling circuit and the heat reject circuit is both dryer (because of condensate removed) and warmer and re-enters the remaining 'untreated' passing foggy air, immediately evaporating any remaining water droplets and clearing the air of all fog.

Psychrometric process

The process is efficient and effective for fog as the air is already fully saturated, and most of the energy consumed on the chiller side is used to remove latent heat (water vapour), not reduce ambient air temperature. The latent heat removal (from the evaporator coils) and the equivalent addition of sensible (dry) heat (from the condenser coils), as well as any additional mechanical heat produced in the process, creates a dryer air mixture than by direct heating alone with the equivalent amount of power used as a heater.

An illustrative example of the dehumidification process on a psychrometric chart is shown in Figure 4. In this example, humid air at 150 m^3/s @ 20°C, 95 per cent humidity (POINT 0) has a 33 per cent portion of the main airflow (50 m^3/s) directed through refrigeration (650 kW using 175 kW power POINT 1) and then reheated (825 kW POINT 2) before finally remixed with the untreated main airflow (POINT 3). The combined air is well inside the fog-forming region and considerably lower in both relative and absolute humidity than the starting condition. Any fog remaining in the untreated air stream is evaporated and quickly cleared.

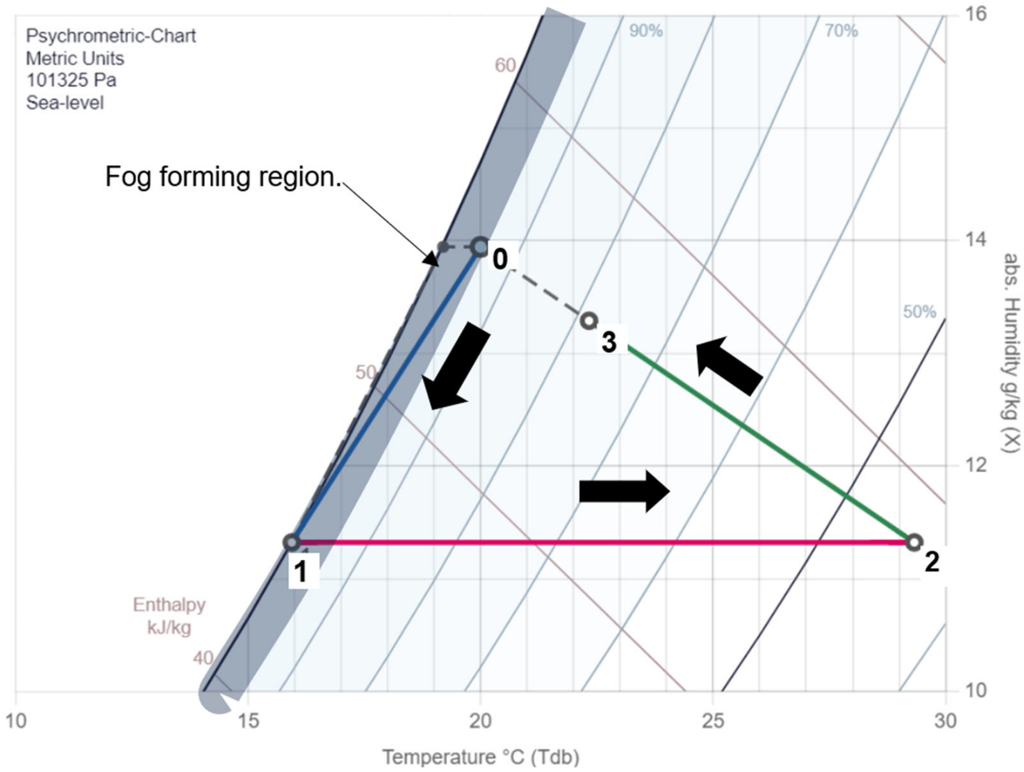

FIG 4 – Psychrometric chart showing dehumidification process (www.psych-chart.com).

Design considerations

The refrigeration design on the condenser side uses an air-cooled heat exchanger as opposed to a water spray-cooled system that would add moisture to the air. The evaporator side could potentially use either a fan-forced coil-finned evaporator or a chilled water system with cooling towers or spray chambers, as both systems will condense and remove water vapour from chilled moist air. The selection of the cooling technology may depend on air and water quality and other factors such as cost, space, efficiency, maintenance and cleaning.

Given the location is likely to be in or near a travel ramp, the size of the apparatus may need to be modular and compact to allow easy placement along the roadway or within a side tunnel without the need to mine extensive chambers. Systems may need to be repeated along the ramp at strategic intervals, particularly if made smaller to fit into tight locations.

An example system adjacent to a main ramp is shown in Figure 5, where a portion of the ramp airflow is drawn in by fans through the intake cooling coils, reheated from the chiller compressor reject, and then injected back onto the ramp to mix with the remaining foggy air. Cold water condensate is generated which would typically be discarded to the drainage system.

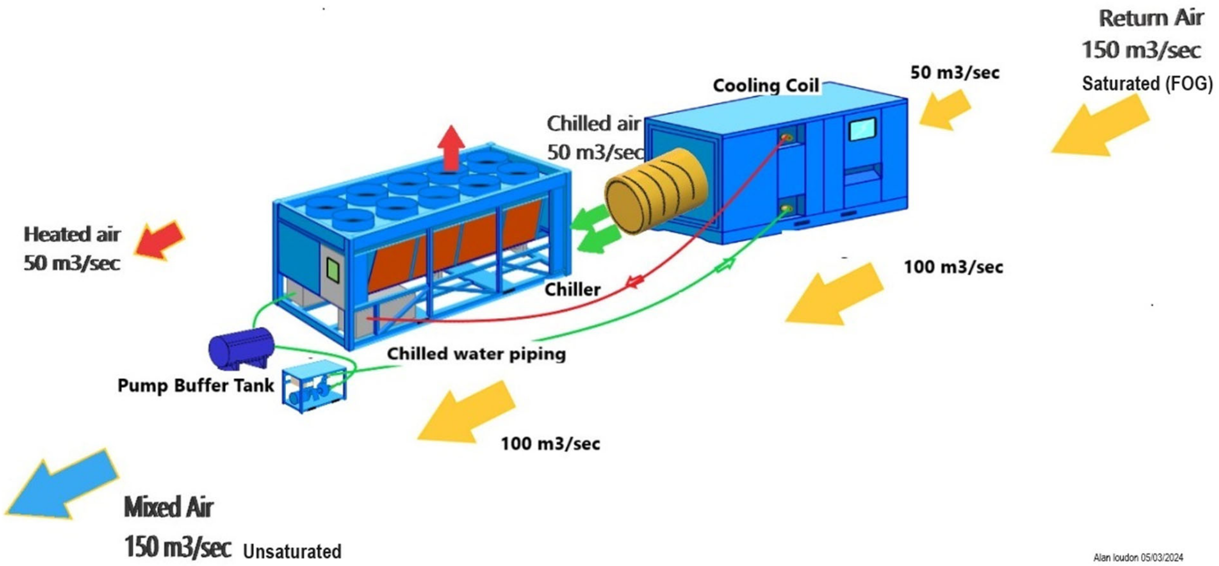

FIG 5 – Example layout of an underground refrigeration dehumidification system.

Another consideration is whether the modularity of the system could be reconfigured and relocated for refrigeration instead of dehumidification at warmer times of the year when fog may not be present.

EFFICIENCY AND EFFECTIVENESS

To determine the potential viability of fog removal, modelling is used to analyse and compare a mine dehumidification system to a base comparative electrical heating system that provides similar fog removal potential.

Modelling methodology

A series of models were created in Ventsim™ using refrigeration plant performance data supplied by Howden Australia. The modelling aims to treat thick foggy air so that the atmosphere remains clear for more than one kilometre further up the ramp, with both a refrigeration system and a conventional electric heating system to compare power consumption and effectiveness.

Ventsim's thermodynamic simulation capability includes fog modelling (Griffith, 2021). The software calculates water condensate formed from cooling saturated air during simulation and transports liquid condensate water within the airflow mass up to a maximum concentration limit. The transported condensate is allowed to re-evaporate if heat is added or it is mixed with dryer air. If condensate exceeds 1200 mg/m^3, coarse droplets are assumed to 'fall out' limiting further water accumulation. Modelling by the author at numerous cold climate mines has validated the fog modelling results, provided humidity is correctly calculated using appropriate wetness fractions, diesel equipment inputs and heat assumptions.

The use of a full thermodynamic network modelling approach instead of simple psychrometric analysis has several advantages as it considers other external factors such as downstream heat loss to the surrounding rock strata, additional moisture evaporated from roadways and wet surfaces, and water vapour added from diesel equipment exhaust and activities.

In addition, not only the effectiveness of fog removal can be examined, but also the distance the air can remain fog-free in an upcasting ramp airflow environment. This allows a more realistic comparison of fog reduction effectiveness, given the differing temperature outputs of a direct heating process versus a dehumidification process.

To achieve this goal, a hypothetical cold climate mine is modelled for both technologies:

- Diesel equipment and warm humid air is upcast through a ramp at 150 m^3/s.
- Different ambient saturated ramp air temperatures (10°C, 15°C and 20°C) with moderately heavy fog eventually forming (proposed at 400 mg/m^3 in density at the test site) are tested to compare process efficiencies and effectiveness at different air temperatures.
- Airflow of 50 m^3/s (one-third of the total) will be diverted and treated by dehumidification and remixed downstream with the remaining air on the ramp.
- Howden Australia has provided technical specifications for the performance of a typical refrigeration spot cooling unit.
- The heater system applies sensible heat only and is equalised by iteratively adjusting the output until giving the same fog-free distance as the dehumidification system (Figure 6).
- The resultant power consumption and budget capital costs between each equivalent system will be financially compared.

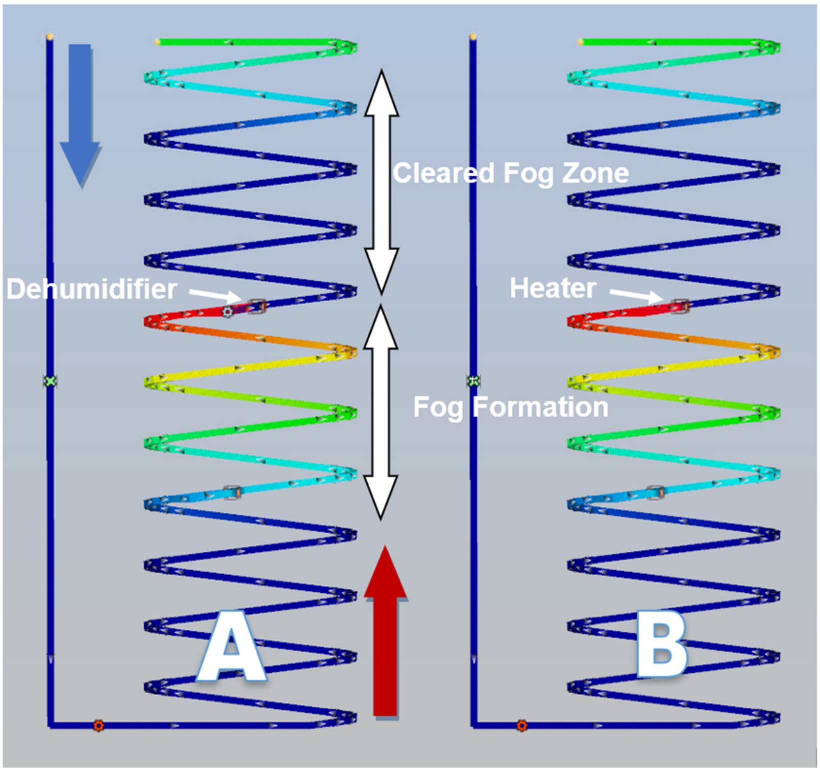

FIG 6 – Ramp cross-section view showing fog modelling of refrigerative dehumidification (a) equalised with direct heaters (b) in Ventsim™ (colour showing fog density, dark blue = clear of fog, red = thick fog).

The modelling arrangement shown in (Figure 6) demonstrates the modelling output of a refrigerative dehumidifier versus an electric heater sized to give the same fog removal distance and performance.

The colours show the relative fog concentration, with dark blue at 0 mg/m^3 (clear) and thick fog in red at approximately 400 mg/m^3.

RESULTS

The results in Table 1 summarise the fog reformation distance at which the fog reaches 50 mg/m^3 (considered a light fog with reasonable visibility) and the distance at which the fog returns to the pre-treatment concentration of 400 mg/m^3, together with output temperature and consumed power data.

TABLE 1

Modelling results for refrigerative dehumidification (Refg) versus electric heaters (Heater).

Item	Unit	CASE A		CASE B		CASE C	
Ramp temperature (100% RH)	°C	10.0		15.0		20.0	
Initial fog concentration	mg/m^3	400		400		400	
Ramp clear distance (<50 mg/m^3)	m	1000		1100		1100	
Ramp clear distance (<400 mg/m^3)	m	2400		2300		2200	
Heater kW to Refrig Power kW ratio	ratio	3.87		3.81		3.83	
		Refg	**Heater**	**Refg**	**Heater**	**Refg**	**Heater**
Discharge conditions	wb	11.7	15.7	16.8	21.4	21.6	25.3
	db	18.1	23.3	26.9	33.1	33.1	38.2
	RH	44%	45%	33%	35%	34%	36%
Ramp mixed conditions	wb	10.8	12.1	15.6	17.4	20.5	21.9
	db	13.3	13.8	19.0	20.3	24.4	25.2
	RH	84%	83%	77%	76%	77%	76%
Moisture removed	mL/sec	110	0	179	0	204	0
Process input electrical power	kW	212	840	295	1125	300	1150
Refrigeration produced	kWr	496		717		729	
Estimated CAPEX	$k	450	150	450	200	450	200
Annual power cost (0.10 c/kWh)	$k	186	718	258	985	263	1007

Both refrigeration dehumidification and electrical heating can provide effective ramp fog-clearing results over a significant length of the ramp, however, the dehumidification process uses only 26 per cent of the energy of the heater for the same result.

The refrigeration system showed similar fog removal performance for temperatures between 10°C and 20°C. While a decrease in plant performance was noted for colder temperatures (10°C), the fog clearing distance remained similar likely because of the reduced water vapour carrying capacity of colder air and reduced evaporation of water along the roadways.

DISCUSSION

A refrigerative fog removal system is more efficient, using only a quarter of the power of equivalent electric heaters. While still arguably high in energy and capital costs, the payback period is less than six months compared to using electric heaters. The justification for installing a fog removal system will rely on the mine requirement to control visibility safety hazards, protect infrastructure and electricals from moisture and gain productivity improvements from improved traffic access and speed.

The practical challenges with using a refrigeration system for fog removal will be to design an efficient, compact, low-maintenance system that limits fouling or frequent cleaning requirements. In exhaust conditions with fumes and dust, coil fin heat exchangers will likely require regular cleaning, although a chilled water spray chamber or cooling tower could be used instead if space was available.

No attempt was made by Howden Australia to improve the efficiency of the plant for fog removal applications or maintenance and further inroads could likely be made here with detailed engineering design and optimisation. In addition, mechanical aids such as mesh droplet removal or filtering before the intake may provide a more efficient process and also help remove products that would otherwise foul refrigeration coils.

While only one plant size and airflow application were modelled in this research, a system can scale accordingly so dehumidification could be sized and distributed at strategic locations at the mine.

CONCLUSIONS

Refrigerative dehumidification for the removal of fog in underground mines appears to be an effective application of proven processes. The dehumidification process consumes only one-quarter of the energy of a comparable direct electrical heating system and provides a more effective and longer-lasting fog removal effect than some other methods such as mechanical filters, screens or mesh.

In summary, the use of refrigeration technology to remove fog in underground mines is likely to be more effective and more economically viable compared to existing non-refrigerative methods that have been previously researched, however, practical field test work would be required to confirm performance assumptions and ensure practical issues such as maintenance and cleaning can be reliably achieved.

ACKNOWLEDGEMENTS

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