Arctic mine air heating

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Northern mines use robust mine air heaters that can withstand the rigors of operation in such a harsh environment. Today's mine air heaters are complex systems with fully automated PLC controls and remote communications. Innovative combustion and heat transfer technologies are normally employed to maximize efficiency and performance. Sizing and selection of such heat processing systems is based on safety, reliability, efficiency and serviceability.

In extreme environments such as the Canadian arctic, efficient operation of mine heaters can be quite complicated and even the most efficient system has the potential to burn through considerable energy inputs at significant cost. It is therefore prudent to optimize the heating system settings to eliminate business waste.

A scientific methodology for optimizing the operation of heat processing equipment is introduced in this paper. A psychrometry based model was developed as the method of effectively controlling the mine air supply state point. The theoretical limits of the mine air heaters are discussed in terms of psychrometry to propose an optimized system operating point. Some of the practical considerations and methods proposed to guarantee safety and to manage the operational risk in harsh arctic environments are considered. A method using climate normals and heating degree-days is introduced as a basis to evaluate the overall system performance. These tools show promise for forecasting and budgeting, considering the variable effects of the weather.

A case study is presented to demonstrate how system air heating performance can be maximized and heating costs reduced using the proposed methodology.

Keywords: Arctic, mine air heating, underground ventilation, ice, psychrometry

1. Introduction

Like many other facets in mining, the goal of mine air heating is to create a safe environment for the workers, the equipment, and facilitate an efficient extraction of the resource – in that order. Unlike a residence or an office building, the goal is not the comfort of the workforce.

The ultimate goal of optimizing the mine heating system is to reduce the energy consumption, which is a significant operating cost. Additionally this has significant environmental benefits: directly reducing the production of carbon dioxide and other contaminants that would have otherwise been released into the atmosphere.

A scientific methodology for optimizing the operation of heat processing equipment is introduced in this paper, and a case study is presented to demonstrate how the proposed methodology can be effectively used to maximize the system air heating and reduce heating costs.

2. Heating and psychrometry

The primary governing factor for mine air heating is to prevent the formation of ice in areas that would create a hazard or damage equipment and infrastructure.

2.1 Forming ice through autocompression

In some mine ventilation systems the air mass will create fog and start to deposit frost and ice on the walls. This can occur when warm humid air undergoes a process of autocompression as the air travels up a ramp, a shaft, or otherwise increases in elevation. The sensible heat and dry bulb temperature reduce to a point where the air mass reaches its water saturation limit, the excess water is then precipitated as fog or airborne ice crystals. If there is a surface temperature below 0 °C (32 °F) present a deposit of frost and possibly thicker ice will start to develop.

Reduced visibility caused by the fog can create some significant issues for mobile equipment. Some mines have used track lighting systems to either mark the center of the travel way, or the side walls, as an aid to the drivers. Additionally traffic control lights can be used to minimize the potential for oncoming traffic in the affected areas. It is also common to disallow pedestrians in areas of low visibility.

Mines in a temperate climate will experience this issue in the most extreme cold months of the year at or near a portal and it can be generally managed without too much concern. Occasionally mines have managed these issues by seasonally reversing the ventilation direction.

This situation may also occur in an exhaust shaft near the surface, but it may be completely inaccessible and therefore undetected. In this situation a prudent control

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would be to monitor the exhaust shaft resistance using some differential pressure instrumentation.

Perhaps the most dangerous situation is when this occurs in a shaft during a sinking operation. The formation of ice on the walls, the Galloway, the collar, or inside the head frame presents a serious risk to any worker below. Therefore it is important to prevent ice forming conditions in this environment. If a fog begins to form, it becomes very important to monitor these locations for any potential ice.

In an arctic mine constructed in the permafrost zones, the potential for ice formation may be increased because it can occur at increasing depths. All of the principles discussed above are still the same. However, there is an increased risk by developing ice and having it continue to grow from one year to the next.

Another situation that may present a serious safety hazard is if ice is allowed to form over a period of time and then the conditions rapidly warm. This may happen when a surface ventilation raise, constructed and unused for a period of time, is then commissioned, the ice present can warm up and begin to fall. It is conceivable to have tens of kilograms of ice falling over a few hundred meters, which will have very devastating consequences for anything in the line of fire. Raise camera surveys are an important tool to mitigate this hazard.

2.2 Forming ice in warmer temperatures

Under some very specific conditions, it is possible to form ice in an air stream that is above 0 °C (32 °F), which is typically thought of as non-freezing temperatures.

The air mass in an arctic environment is extremely dry. In the Lac de Gras region of the Northwest Territories, Canada the humidity ratio of the surface air is less than 1 g/kg of dry air for over 40% of the year. This corresponds to the saturated water vapor pressure at -15 °C (5 °F) dry bulb temperature. If that air is heated up to room temperature of 20 °C (68 °F) dry bulb temperature using a dry process, the air would be about 8% relative humidity. At a more reasonable mine air heater set-point temperature of 5 °C (41 °F) dry bulb temperature, the air would be approximately 20% relative humidity. Liquid water evaporates very quickly under these conditions.

The process of evaporation is a powerful form of heat transfer. The water surface evaporates which is driven by the forces of equilibrium. This is an energy transfer to the vapor phase (latent heat of vaporization) from the water that remains in the liquid state reducing its sensible heat, therefore creating a localized reduction in the water temperature. This evaporation process can be so significant that the liquid water is locally cooled to the point of freezing, which releases more energy (latent heat of fusion), which is also consumed by the evaporation.

This is the same effect that will be experienced using a damp towel on your neck while trekking through the Australian outback or possibly in an evaporative cooler (aka. swamp cooler) used in the Mojave Desert. In the arctic however this heat transfer has the power to locally cool the water to the point of creating ice. If this was a standing pool of water then it would eventually evaporate in such a dry air mass and not likely create a significant safety hazard. However if the water is dripping from fractures in the rock, this can be a progressive formation of ice that can present a serious hazard to equipment and personnel.

In many areas of the arctic, permafrost conditions exist only under exposed land and will not be found under lakes that do not completely freeze [1]. Therefore if the orebody extends under a lake or is hydraulically connected to the lake it is reasonable to assume that the mine will experience an inflow of water and would then be considered a wet mine. The experience of the mines in the Lac de Gras area, the permafrost can extend to approximately 200 m depth under the land, but there is a steep transition boundary to unfrozen ground which closely matches the original lake shore boundaries. In the situations where the lake is pushed back using a water retention dyke, the permafrost is only superficial in the areas that were previously under the lake bed.

Only dry mines, which do not experience any water inflow, would be considered candidates for mining in freezing workplace conditions. That is unless measures were taken to artificially eliminate the inflow of water.

The theoretical limit to form ice using this evaporation driven process would be 0 °C (32 °F) wet bulb temperature. The surface effects will change the practical limits that include wall friction generating some sensible heat and counteract the evaporative cooling effects.

Based on experience the authors propose to use a design limit of ice forming potential at minus 1 °C (30 °F) in a location where there is known or a potential source of water.

In a typical mine ventilation network this would correspond to a location at the surface collar of a fresh air raise, some location inside that raise, or in the subsequent drifts that are immediately connected to the fresh air system. The sensible heat, as well as the wet bulb temperature increase as the air mass progresses through the mine ventilation system. That is unless the air experiences the autocompression cooling which was discussed in the earlier section, or the air is mixed with unconditioned air from surface.

Figure 1 shows the psychrometric regions for ice formation. The green zone is above 1 °C (34 °F) wet bulb temperature, where no ice is expected to form. The yellow zone is the transition where ice could begin to form and these locations should be actively monitored for ice. The red zone is everything below minus 1 °C (30 °F) wet temperature and below 0°C (32 °F) dry bulb temperature, where ice formation should be expected. This psychrometric chart has been developed for standard pressure of 101.325 kPa. This chart will be slightly different for locations operating under different pressure regimes.

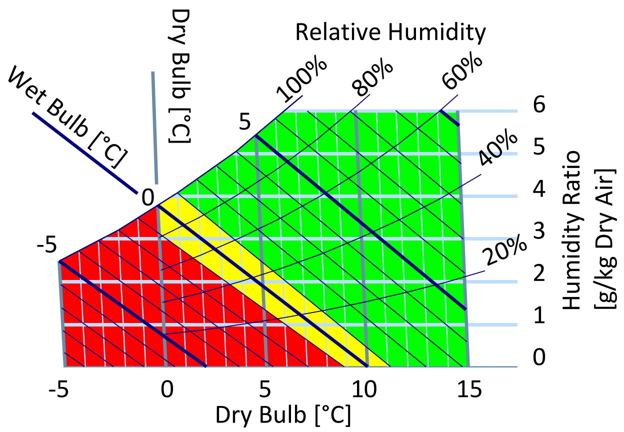

Fig. 1. Psychrometric ice forming regions (adapted from UIGI) [2].

3. Mine air heater technology

Mine air heating technology can be separated into two distinct categories: direct combustion, and indirect combustion.

3.1 Direct combustion mine air heaters

Most mines that require air heating use convenient and relatively clean burning fuels – typically natural gas or propane. This allows a direct combustion configuration. In this type of system the burner and the products of combustion are inside the air stream going underground. Typically these systems are efficient, simple, and reliable options if the appropriate fuel is readily available.

The efficiency of these systems can partly be attributed to the complete capture of all of the products of combustion. Typically contract maintenance is performed only a few times through the year, and few mines maintain the technical experience to completely support the combustion equipment. With the exception of a relatively small maintenance cost, the operation is often only aware of the total fuel costs.

One of the disadvantages of using a direct combustion mine air heater is a baseline of carbon monoxide (CO) as well as other products of combustion is present in the mine. The use of this type of heating system effectively lowers the amount of CO that can be produced by mining activities before reaching the acceptable threshold limit values for a workplace.

Often the only "optimization" of these systems is the result of infrequent tweaking. When a hazard or concern is identified, the set-point temperature is raised. When management focuses on reducing costs, the set-point is lowered and the cycle continues indefinitely.

The authors were unable to find any documented accounts of optimizing these systems using psychrometric principles.

3.2 Indirect combustion mine air heaters

In the Northwest Territories, Canada the operating mines are primarily supplied with bulk materials using a winter ice road which is only open for 8 to 10 weeks a year. These locations are off-grid and the primary source of energy is diesel, which is delivered by super B tankers fully loaded with up to 48,000 to 50,000 liters (12,700 to 13,200 US gal) at a time. Diesel is the preferred choice because it is stable, has a high energy density, and is generally safe to transport and handle.

Diesel fuel is not as clean burning as the alternatives used in the direct combustion mine air heaters. Therefore the burner products of combustion are contained inside a combustion chamber followed by a heat exchanger before being exhausted to atmosphere. The mine air is then passed over this combustion circuit and as a result it should not have any significant contaminants as it enters the mine. Therefore there is no baseline carbon monoxide content as you would have with a direct combustion mine air heater system.

Typically a primary fresh air fan on surface will move more air than a single heater module is capable of conditioning at the peak heating demands, therefore a heater is composed of several heater modules and a plenum building which is then connected to the fan. At Diavik there are five primary fresh air fans (450HP Alphair 10150-AMF-5500 FB 880 rpm), each with six ACI-Canefco mine air heater modules capable of producing approximately 1.65 MW (5.63 MMBTU/hr.) of output heat while consuming about 3.4 L/min (54 US gal/hr.) of diesel at full throttle per module.

The indirect combustion mine air heaters are significantly more complicated than their direct combustion counterparts. As a result the maintenance requirements are also significantly increased. Any operation with these types of heaters should have experienced industrial oil burner mechanic support available on site. Regular maintenance is critical to operating an efficient and reliable heating system.

4. Heat plant efficiency and heating costs

The air mass in the arctic, as discussed earlier, is extremely dry. As a result the specific heat capacity (Cp) of that air is very insensitive to the water vapor pressure. To illustrate this consider an air mass at minus 20 °C (minus 4 °F) at 101.325 kPa standard pressure. The Cp would be 1.0050 kJ/kg·K at 0% relative humidity, and only 1.0064 kJ/kg·K at 100% relative humidity; a difference of significantly less than 1%, which is well within the margin of error in measurement and forecasting. It therefore can be assumed that the energy required to heat the mine air is directly proportional to the mass and the temperature delta (ΔT) for a stable system. Heating-degree-days (K·day) can be used as the demand function for estimating the mine air heater energy requirements. Similar models are commonly used by heating oil delivery companies to estimate demand when contract residential and commercial clients require a refill. The same logic and principles hold that it should be a useful tool to estimate the demands on mine air heating.

The heating degree-day measurement is an integration of the difference between the input temperature (ambient), and the output temperature (raise set-point) over time. A limitation is placed on the integration to represent zero heating-degree-days for any time that the input is higher than the output temperature (negative ΔT). In other terms, if it's warm enough outside then no heat is required and there is no demand for heat.

For example if the average ambient temperature for a day is minus 20 °C (minus 4 °F) and the air is heated up to a set-point temperature of 5 °C (41 °F), then this would contribute 25 K·day to the heat demand function for the day. Similarly if the ambient temperature was above 5 °C (41 °F), then that would contribute zero K·day in demand.

Typically this calculation is performed on hourly data to accurately capture the periods where the temperature fluctuates above and below the set-point temperature. Heating-degree-day values can be calculated on a daily, weekly, monthly, or complete heating season basis.

Figure 2 demonstrates a strong linear relationship between the heating-degree-day and the fuel consumption. This data is from a single fuel pumping system delivering diesel to one of the primary fans equipped with six heater modules. The individual data points were generated on a daily basis over a period of 900 days.

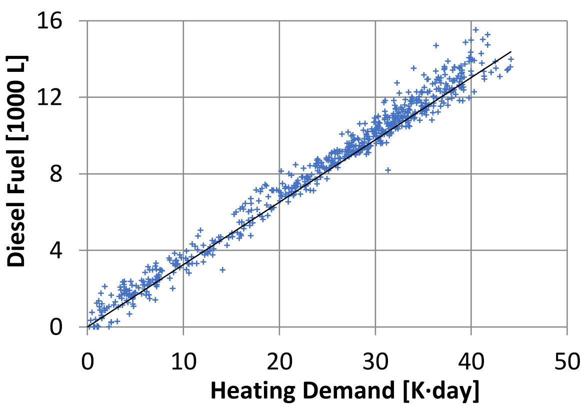

Fig. 2. Fuel to heating degree day relationship.

When heating-degree-days are being used in forecasting, they should be calculated on a climate normal, which represents the "average" year over a much longer period of time. The dataset that is required to calculate this should be high quality measurements of temperature on an hourly frequency over a period of 10 – 30 years, with very little missing observations. Obviously this is a difficult requirement especially in forecasting the heating demands at the feasibility stage of a new property.

Figure 3 shows a climate normal model in the form of a cumulative probability distribution for dry bulb temperature that was developed for the Lac de Gras, Northwest Territories area based on hourly weather observations over a period of 2000 through 2010.

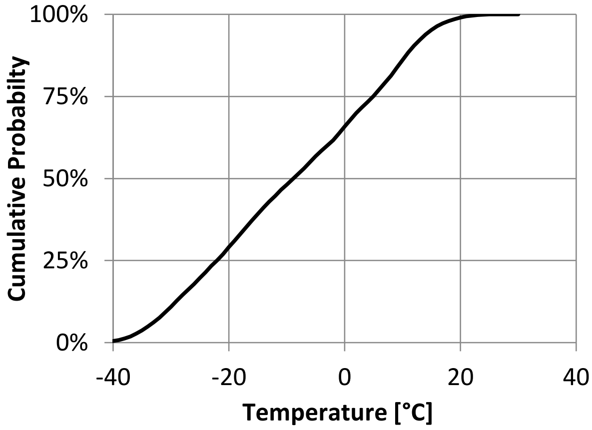

Fig. 3. Climate normal temperature - Lac de Gras.

A relationship of heating-degree-days to set-point temperature is produced as a result of analyzing the climate normal data. Often this kind of data is generated by government agencies for populated areas. An example of this presented in Table 1 for the Lac de Gras region in the Northwest Territories, Canada based on measurements at the Diavik mine site over the period of 2000 through 2010.

Table 1. Heating degree days by set-point.

Raise Set-point Temperature [°C]	[°F]	Degree-days [K·day]
6	43	5946
5	41	5668
4	39	5397
3	37	5132
2	36	4874
1	34	4622
0	32	4378

The relationship between set-point and heating-degree-day suggests that the simple act of reducing the raise set-point temperature from 5 ºC (41 ºF) with a demand of 5668 K·day, down to 4 ºC (39 ºF) with a demand of 5397 K·day, would save approximately 4.8% a year. In this region a change of a couple of degrees Celsius in set-point temperature to an underground mine represents a significant potential savings (or loss) in over a year.

For the purposes of estimating the diesel fuel requirements, the authors have used a nominal 80% efficiency for indirect combustion mine air heaters using an arctic diesel product with a density of 0.85 kg/L at the standard temperature of 15 ºC and a 42.76 MJ/kg net heat of combustion, which was provided by the fuel supplier Petro-Canada. This works out to be approximately 36.35 MJ/L (130,400 BTU/US Gal). The original burner design calculations were based on No.2 fuel oil, with a general heating content of 39.02 MJ/L (140,000 BTU/US Gal). The authors have used the fuel supplier values over the design documents in their analysis. Calculations based on No.2 fuel oil, where a mine is using an arctic diesel product with different properties, can under estimate the fuel requirements.

An estimate can be made of the fuel requirements for any new installation using this data on the fuel, heater efficiency, the required mass flow rate of a designed ventilation system, and an assumed specific heat capacity for the air.

5. Controlling the mine supply air set-point

The mine air heater system is controlled by a local programmable logic controller (PLC). It is advisable that the PLC be also connected to a larger supervisory control and data acquisition (SCADA) system. The value of the SCADA system is to remotely monitor the system performance and collect operating data that can be later analyzed to measure the effects of changes on system performance.

The most basic system control is based on a proportional-integral-derivative (PID) controller. The PID controller uses the process-variable (system temperature) as feedback to achieve a constant set-point value (target dry bulb temperature), by adjusting the control-variable (burner module throttle).

The system temperature is measured at the outlet of the heating plant, typically at the collar of the raise, by one or more long averaging Pt100 resistive temperature detectors (RTD) probes. These RTDs are installed inside perforated steel pipes across the raise for support. The steel structure also helps to smooth the signal measurement due a substantial increase in thermal capacity in comparison to the sensor directly exposed to the flow of the air. The result is a slower reacting signal that is suitable as the process-variable input to a PID controller.

The control-variable is the burner module throttle, which is commonly a 4-20 mA encoded control signal that is transmitted from the PLC to an actuator in the burner. The actuator in turn connects to various valves by way of mechanical linkages to adjust the burner module heat output. The control system would then be able to module continuously between zero (4 mA) and 100% throttle (20 mA).

5.1 Turndown ratio control consideration

Each burner design has a lower limit of heat output, beyond which stable combustion cannot be sustained. This is referred to the turndown ratio, which is approximately 25:1 for natural gas or propane. This means that the minimum heat output at zero throttle is twenty five times smaller than the maximum heat output, hence 4% of the maximum.

Diesel particles need to be atomized into smaller droplets and ultimately vaporized and mixed with a controlled amount of combustion air before it can undergo an efficient combustion. This is commonly accomplished by one of two mechanisms: compressed air assisted atomization with a 10:1 turndown ratio, or a high-pressure fuel nozzle with a 3:1 turndown ratio. The resulting minimum heat production from these types of burners is 10% and 33.3% of the maximum heat output correspondingly.

In the Lac de Gras area most burner modules used in the mine air heating applications are selected to have a design ΔT of approximately 50 K (90 °R) such that they can heat the air from minus 45 °C (minus 49 °F) up to a set-point temperature of 5 °C (41 °F).

Assuming that the burner module is using a high-pressure fuel nozzle design with a turndown ratio of 33.3%, and maximum throttle perfectly heated the air from minus 45 °C to 5 °C. The minimum fire, or zero throttle, would correspond to a system ΔT of 16.7 K (30 °R). The system would not be able to modulate to achieve a set-point temperature when the incoming temperature is above minus 11.7 °C (10.9 °F).

For example, if the incoming air temperature was only minus 3.0 °C (26.6 °F), then the air would be wastefully heated up to 13.7 °C (56.7 °F). Although perhaps a more comfortable working environment, this would be considered a significant and avoidable waste of energy.

In a boiler heating system, or a residential / commercial space heating application, the burners could be controlled by cycling them on and off to control the temperature in the lower zone. Unfortunately by the nature of the burners and the demands of the underground mining environment, this is not a viable option.

Instead the PLC controlling the system needs to shut down some of the burner modules in the system – a process called staging. If the system in the above example had an incoming air temperature of minus 3.0 °C (26.6 °F), the system could shut down four of six heater modules connected to the system. Assuming the air flows across each heater module were equal, this would result in 33.3% of heated air from two modules at 13.7 °C (56.7 °F) mixing with 66.7% of unheated if the modules were at zero throttle. The result would be a mixed air mass with temperature of approximately 2.6 °C (36.6 °F) at 0% throttle. This is below the set-point temperature given in this example of 5 °C (41 °F), but the burner module throttle on each of the two operating burners can easily be modulated by the PID loop to achieve the required set-point temperature.

Another one of the critical functions of the PLC system is to provide a series of protection systems of interlocks to increase safety to the workforce, and prevent unnecessary damage to the equipment and infrastructure. Perhaps the most important controls are the over-temperature sensors and the carbon monoxide sensors, both which are intended to shut-down the fresh air system in the event of a fire to minimize smoke and other contaminants from entering the mine fresh air system.

6. Proposed methodology for optimization

The process of optimizing a mine ventilation system is inherently a process of continuous improvement. A structured process: define, measure, analyze, improve, and control (DMAIC) can be a valuable tool to use when making improvements to the mine air heating system.

6.1 Define

The goal is to reduce the fuel quantities required to heat the mine air. The primary inputs are: incoming air temperature, the heating set-point temperature, the air flow quantity, and the system efficiency. The incoming air temperature is beyond control, and quantity of the air flow is considered out of the scope of this investigation. Only heating set-point temperature and changes to the system to improve efficiency can be made to optimize the arctic mine air heating system.

6.2 Measure

The mine air heating system is complex and variable. As a result it requires some effort to ensure that the process variables are being measured correctly. The airflow sensors require periodic calibration using a pitot traverse. Fuel flow sensors require calibration and require consistent configuration (eg. temperature / density corrected measurement or standard density). The ambient temperature probes must be shielded from the radiation effects of sunlight, and not buried in snow drifts. The raise air flow temperature sensors should be long averaging sensors to provide a reasonable cross section of the air flow. Ideally the output temperature sensor would be placed at some reasonable distance down-stream to allow for a nearly complete mixing of the heated air, but this is limited by physical access and other practicality considerations.

6.3 Analyze

The core of the analysis at a high level can focus on a measure of fuel consumption intensity. The authors would propose using the consumption rate in liters [L] and normalize that on air flow rate [m^3/s], and heating demand degree-days per day [K·day]. The resulting units of intensity would be in [$L \cdot s/K \cdot day \cdot m^3$].

Assuming a standard density of 1.20 kg/m^3, Cp of 1.0050 kJ/kg·K, net heat of combustion of 36.35 MJ/L, and a nominal efficiency of 80%, and a constant 86400 seconds per day, the idealized fuel consumption intensity is calculated to be 3.58 $L \cdot s/K \cdot day \cdot m^3$.

The authors have found that using a measurement of fuel consumption intensity is more useful than back calculating an efficiency. The cumulative effect of assumptions and measurement errors makes the calculated efficiency differ from the true efficiency. The difference between true and calculated efficiency can create unnecessary confusion for those who are not familiar with the process.

Trends of the fuel consumption intensity have successfully been calculated on monthly, daily, and hourly intervals. The longer time intervals have the benefit of smoothing out the resulting data.

Although this is the preferred analysis to evaluate system changes, it does not provide meaningful insight into the effects of lowering the set-point temperature, which is also a significant system improvement. The value of the changes to the set-point can be inferred from the heating degree-days by set-point temperature basis discussed earlier.

6.4 Improve and control

As a result of the data analysis a list of potential improvements can be generated. This will typically include a mix of mechanical changes, maintenance strategies, and changes to the process controls. These will need to be evaluated and prioritized. Incrementally systematic improvements can be made. A process of continuous improvement is used where following the changes data is collected, analyzed, and this is repeated.

7. Areas for improvement

It has been the experience of the authors that areas for optimizing mine air heating fall into one of four categories, described below.

7.1 Obvious

These project areas include insulating ducting, and correcting other known issues with the system. Often these are not controversial and very obvious changes. Therefore they do not benefit from the aforementioned DMAIC process. One of the first goals to be addressed in this category is to improve the system stability. This specifically includes ensuring that the heating system does not have significant departures from the set-point temperature.

7.2 Process control

The most significant improvement that can be made to the process control is by optimizing the set-point temperature. This starts by identifying the critical locations in the ventilation system, and making system adjustments to reliably achieve the required heating, while eliminating the waste associated with overheating the air.

7.3 Combustion & mechanical

Improvements can be made to the combustion and mechanical operation of the heating plant. These are generally well understood and documented by the equipment manufacturer and other specialists.

One of the most significant changes that can be made is by reducing the amount of excess air provided by the combustion blower, and increasing the residency time of the products of combustion in the heat exchanger. It may be possible to reduce this enough to create a condensing environment inside the heat exchanger. The efficiency gained is by recovering the latent heat of vaporization from the exhaust water vapor that would have otherwise been lost. The condensate that develops inside the burner needs to be removed from the system through drains, collected and disposed of properly. Additionally there is now the possibility that some localized parts of the heat exchanger may start to develop ice, which could cause other inefficiencies and potential damage.

7.4 Preconditioning

There exists the possibility of harvesting energy from other sources and using that to precondition the incoming air in advance of the mine air heaters.

The Macassa mine in Kirkland Lake, Ontario, Canada pre-heated their mine air using energy recovered from the mine water and compressor systems. [3]

Other authors have proposed recovering heat from the mine exhaust systems. [4]

Remote arctic mines typically have a surplus of waste heat from the diesel electrical generation facility, especially in the summer months when there are few requirements to heat buildings. It might be economically feasible to create a borehole thermal energy storage facility and recover this for the mine air heating season.

There possibly exist many more site-specific novel sources of low grade energy that can be harvested. Based on the set-point heating degree-day relationship developed above, a few degrees are all it takes to create some significant potential energy savings. Some early design decisions before construction begins may create or eliminate these potential opportunities. It may be very lucrative to consider these opportunities early in the project design stages.

8. Case study

Over the past few years the Diavik Diamond Mine has been implementing various energy improvement projects in an effort to reduce the overall mine operating costs. The mine air heating system currently represents the largest consumer for diesel on site after the power generation facility.

A substantial list of deficiencies and opportunities was generated for the mine air heating facility. These were subsequently ranked and significant effort has been made in reducing the diesel consumption at this facility. This included insulating ducting, developing a burner hour-based maintenance strategy, improving instrumentation and control strategies.

Figure 4 shows the trend of the fuel intensity as calculated monthly for the mine-wide fresh air heating facility. The majority of improvements occurred at the end of the 2013-2014 heating season, and before the start of the 2014-2015 heating season. Part of the change in this trend has been attributed to an improved instrumentation and as such would not be realized as savings.

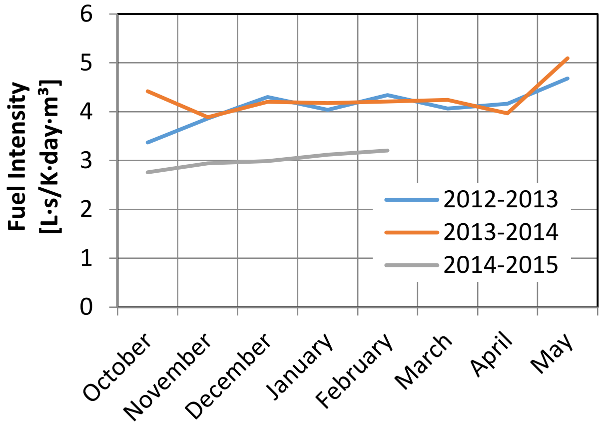

Fig. 4. Heating fuel intensity by month.

Additionally the raise set-point temperature has been systematically lowered from 6 °C (43 °F) down to 4 °C (39 °F) on three of the five primary fresh air fans. The remaining two fans require some control changes as a prerequisite before the set-point temperature can also be lowered. Preliminary data suggests that the savings are in agreement with the heating-degree-days predictions.

A monitoring program has been developed to identify any ice forming in the fresh air raises before it presents a significant risk to safety or damage equipment. This includes periodic inspections of the fresh air raises using a raise camera system, online monitoring of raise pressures. The critical location was identified near the bottom of the raise, where water is present. This location has been instrumented and is being monitored for wet bulb temperatures. Following the set-point temperature reduction, the temperature measured at this critical location fluctuates between 0 °C (32 °F) and minus 1 °C (30 °F) wet bulb temperature, which is at the limit of where the formation of ice can be expected.

To illustrate the potential savings associated with the set-point change, assume 125 m^3/s (265 kcfm) air flow rate per primary fan. The fuel requirement can be predicted using idealized fuel consumption intensity is calculated to be 3.58 $L \cdot s/K \cdot day \cdot m^3$ that was developed earlier, and the heating-degree data in Table 1. For a 6 °C (43 °F) set-point base case, 2.66 million liters of fuel would be required over the course of an "average" year to heat the mine air per fan. Reducing the set-point to 4 °C (39 °F) would only require 2.42 million liters per fan, a 9.2% savings in fuel. At the time of writing this the price at the pump for diesel in Yellowknife, Northwest Territories, Canada is approximately 1.25 $/L. Using that price, the savings would be in the order of $300,000 annually per fan.

9. Conclusions

Arctic mine air heaters represent a significant cost to an operating mine. The heating-degree-day basis has been shown as a useful tool in predicting changes, and forecasting fuel consumption. Using the proposed systematic approach to improving the mine air heater system can generate significant savings. These savings can be realized by reducing the set-point temperature, and improving the system control. Other improvements can be made in the areas of mechanical, combustion, and potentially energy harvesting. The case study illustrates that small percentage point improvements can have significant financial and environmental impact for an operation.

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