Hydraulic Air Compressor (HAC) Demonstrator Project

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ABSTRACT

The Hydraulic Air Compressor (HAC) Demonstrator Project will measure and verify the electricity savings potential of new HAC technology primarily for deep mining applications. A 30-metre high HAC Demonstrator rig will be installed in a former elevator shaft at Dynamic Earth, Science North's earth sciences centre in Sudbury, Ontario, Canada. Conventional mechanical refrigeration systems for deep mining applications (below 2,500 metres) consume significant amounts of electricity and add considerable costs to mining operations, impacting mines' competitiveness. HACs offer a more energy efficient and reliable approach to air compression, but have historically relied on the existence of a nearby water course, preventing their use in deep mining applications. Key innovations of this new HAC technology – including the use of open and closed loop configurations (no nearby water course needed), co-solutes, temperature manipulation and alternative gases – have yet to be proven in a large-scale, real-world environment. Project partners include the Centre for Excellence in Mining Innovation's Ultra Deep Mining Network, a business-led Network Centre of Excellence and MIRARCO, a not-for-profit research and development organization owned by Laurentian University. The paper will provide details on the new HAC technology and its preliminary performance results, and will outline the business case for adoption of the technology with potential applications in the fields of deep mine cooling, carbon capture, air conditioning and general industrial gas compression. The project is currently underway and final results are expected mid-2018.

A (re-)introduction to Hydraulic Air Compressors

Historical landscape

Over a 33 year period starting from 1896, 18 hydraulic air compressor were constructed, with delivery pressures ranging from 1 bar to 8.2 bar gauge (15 to 120 psi), free air deliveries ranging from 30 to 51,000 Sm^3/h (18 to 30,000 Scfm) and delivered air power ranging from 2 to 3,251 kW (Langborne 1979; corrected as reported by Pavese 2015 and Pavese, Millar, and Verda 2016). These systems utilized renewable hydropower resources. Leets and penstocks delivered water to air-water 'mixing heads' of varying designs, but which would be described as an 'eductor' or 'ejector' in modern parlance, e.g. Huang et al., 1999. The velocity of the water (the primary or motive fluid), relative to that of air bubbles, is sufficiently high in these devices so that drag on the bubbles inducts them downward. By the Bernoulli equation, potential energy of the water is converted to pressure energy as the water descends into a vertical 'downcomer' duct, and this pressure is transmitted to the air bubbles so that they are compressed. At the base of the downcomer, gravity or centrifugal gas-liquid separators produced a stream of dry, cool, pressurized air that was piped to the demand centre, and a second stream of air bubble-free water that ascended a so-called 'riser' duct and returned to the water course via a tail race section. Other than gate valves to shut off incoming water flow, these devices had no moving, mechanical parts, required no lubricants (and hence produced oil-free air) and were extremely reliable machines. The historical HAC installations operated for decades, maintenance-free, and in many cases, they outlived the design lives of their demand centres (Table 1).

Figure 1.The HAC constructed at Ainsworth, British Columbia in 1898, with air power rating of 431kW, utilizing head of ~33 m head, ~1.9 m^3/s water and producing 2.2 Sm^3/s (4667 Scfm) air at 6 bar gauge (Pavese, Millar and Verda 2016). This HAC is reported to have provided air to the Kaslo Copper Mine, 2 to 3 miles away from the installation (H 2016).

Table 1. Operating lives for historical HAC installations (*Shut down due to mine closure)

Location	Operating Period	Operating Life [yrs]	Source
Dominion Cotton Mills, Magog, Quebec, Canada	1896 - 1953	57	Dumaresq 2009
Ainsworth, British Columbia, Canada	1898 - 1911?	13*	Schulze 1954
Norwich, Conn., USA	1902 - 1929	27	Schulze 1954
Trent Canal Lift Lock, Peterborough, Ontario, Canada	1904 - 1967	50	Schulze 1954
Victoria Mine, Ontonagon County, Michigan, USA	1906 - 1921 1929 - 1930	16*	Schulze 1954
Ragged Chutes, Nr Cobalt, Ontario, Canada	1909 - 1981	72*	Moore et al. 1982
Persberg, Sweden	1915 - 1954	39	Schulze 1954

The HAC advantage - isothermal compression

Performance test results of these historical systems are available within the literature (Frizell 1880, Bernstein 1910, Judd 1908, Markman 1928; Schulz 1954), and report that the hydropower to pneumatic power conversion efficiency is high, ranging between 53% and 88%, although these figures have been corrected by Millar (2014) and Pavese (2015) to 40% to 78% to allow for gas solubility effects, which seem to have been underappreciated in some of these historical determinations. Conversion efficiency was not a primary concern of HAC pioneers because the input energy, being renewable hydropower, had close to nil marginal cost.

Re-analysis of the historical, published data, direct experiment on a recent pilot scale (5m high, ~10 kg/s water) HAC and energetic and exergetic analysis all confirm that the compression process in the downcomer of a HAC is '*nearly isothermal*' (as formalized in Pavese, Millar and Verda 2016.); gas temperature rises of a few mK can be expected. Isothermal compression of a gas is the thermodynamically minimum work gas compression process (see, for example, Eastop & McConkey 1993 or Rogers and Mayhew 1992). In a HAC downcomer, the high interfacial area between the liquid and gas phases, the high heat capacity of water and the ~10^3 times greater mass flow of water relative to the gas result in a single stage, continuous (<u>not</u> multi-stage) compression process that involves contemporaneous work transfer to the gas and heat transfer to the water and practically leads isothermal conditions, declared as unattainable ideals by the same authoritative texts. This renders the achievements of the historical HAC installations even more remarkable: as well as exploiting renewable hydropower resources for economic effect, this was executed with the most energy efficient hydropower to pneumatic power conversion process conceivable.

A further advantage of HACs reported by Schulz (1954) was that the compressed air produced by them was, somewhat counter-intuitively, drier, than compressed air produced by the mechanical compressors of the times. The reason for this is that the saturated vapour pressure of water in air reduces as the air pressure increases and so the water vapour condensed and joined the bulk circulating water flow in the downcomer process and was removed in the HAC's air-water separator device.

Performance trends of historical HACs

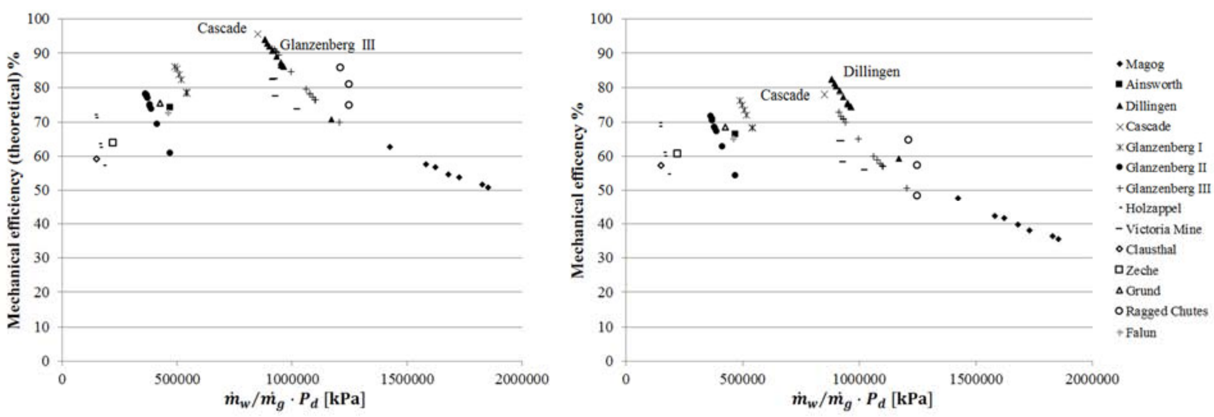

Figure 2. Theoretical and overall mechanical efficiency of 14 HAC installations, plotted against the product of mass flow ratio of the two phase (water, air) bubbly flow and delivery pressure.

The delivery pressure of a HAC is essentially fixed by the difference in elevation between the water / gas level in the physical separator device at depth and the elevation at which the water returns to a watercourse at the tailrace. The velocity of water in the riser column is sufficiently low such that dynamic pressure can be neglected so that delivery pressure is determined by the static column of water between these two elevations in this single phase flow duct. A HAC system consumes the available hydropower by i) overcoming irreversibilities in the air-water mixing process and the air-water separation process, ii) overcoming frictional losses of the fluid rubbing on the duct surfaces, iii) overcoming dynamic losses associated with sharp turns, sudden changes in flow cross-sectional area, etc. iv) drag between bubbles and water, and v) compressing the gas.

For a given admitted water mass flow, travelling between forebay and tailrace elevations (which are typically ~ 10^1 m: low head situations), a HAC system permits admission of precisely the right amount of air mass flow to balance these 'losses' i) to v), subject to the atmospheric pressure boundary conditions at forebay and tailrace. The air-water mixing head does not regulate the flow, it simply presents a given amount of irreversibility. A system energy balance determines the amount of air inducted; an air water mixing head may not even be necessary. If the water mass flow rate is adjusted, the HAC physically re-balances the cycle energy equation by admitting more or less air to compress. Although the loss components i) to iv) are generally quadratic with velocity, their magnitudes in well designed HACs do not vary greatly so that the efficiency of conversion varies inversely proportionally to the water mass flow rate, as is evident in the performance data of individual HACs presented in Figure 2. Taken together, these performance data also suggest a pareto-optimal HAC efficiency around 75% after gas solubility effects are taken into account, and 85% if solubility effects can be suppressed.

Open loop and closed loop HAC systems should be run 'hot' and 'salty'

Gas solubility in water increases with pressure (King 1969, Battino, Rettich and Tominaga 1984, Sander 2015), and this effect has been reported in HACs (EBW 1910, McNair and Koenig 1911) and analysed for HACs by Chen and Rice (1982, 1983), Millar (2014), Pavese (2015) and Young (2017). The problem for HACs is that some of the air dissolves in the water and thus by-passes the air-water separation process, reducing the mass flow of air at outlet, in comparison to that at inlet. Pavese, Millar and Verda (2016) report compressed air yield (ratio of air mass flows: out/in) varying between 73% and 97% for the historic HAC fleet, where the highest yields are achieved by relatively high head, low flow rate HACs, and the lowest yields were returned by relatively low head, high flow rate HACs.

The effect of solubility physics on the design of HACs is amplified in Millar, Trapani and Pavese (2016) where a 'WaveHAC' design is presented to exploit the ultra low head (~ 1.25m) available by permitting offshore water waves to run up into a forebay reservoir engineered with floating hull. Design optimization studies reported therein associate a maximum downcomer diameter and a maximum downcomer length with the ultra low head. Such systems are dominantly constrained by the solubility physics. The greater is the water mass flow, the greater is the chemical potential for the gas to dissolve as the pressure increases. In the high head, low flow rate HACs of the historical fleet, gas species must have approached saturation conditions quickly to return the highest yields.

Although it does not represent a hydrodynamic loss, as in i) to iv) above, the effect of gas solubility on HAC performance is evident in the expression for their overall efficiency in, extrinsic, power terms:

$$\eta_{mech} = \frac{\dot{W}_{ind}}{\dot{W}_{input}} = \frac{\dot{m}_{G,out}\int V dp}{\dot{m}_{G,in} w_{12}} = \frac{\dot{m}_{G,out}}{\dot{m}_{G,in}} \cdot \frac{\int V dp}{w_{12}} = y \cdot \frac{\int V dp}{w_{12}}, \tag{1}$$

where it may be appreciated that the overall mechanical efficiency is the product of the yield and the intrinsic thermodynamic efficiency (expressed in units of J/kg). The overall mechanical efficiency falls in direct proportion to the yield. For run-of-river, renewable hydropower HAC systems, the inevitable consequences of the solubility physics simply must be accepted. Open or closed loop HAC systems economically exploit the high compression efficiency of the nearly isothermal process alone and artificially maintain the head between forebay and tailrace reservoirs with pumping. For these HAC systems, based on the work of Ruckenstein and Shulgun (2002), Millar (2014) suggests that the undesirable effects of the solubility physics on HAC performance may be suppressed through the addition of co-solutes to the circulating water, and by reducing the dissipation of compression heat held in the circulating water. This has been confirmed analytically through simulations by Young et al. (2016), and more completely in Young (2017).

Young's (2017) simulations also suggest that as water containing dissolved gas ascends and depressurizes in the riser duct, so the gas will exsolve from the water and potentially present an 'air-lift' effect: an effective return of useful work corresponding to the solubility loss in the downcomer. The clearest evidence for such an effect from the historical HAC fleet, is an account from Schultz (1957), that reports the water returning to the water course at the Ragged Chutes HAC being 'milky' in appearance. As far as the authors are aware, other than in Young (2017) there are been no reports of efforts to quantify this effect, which, if it is proven to exist through direct and practical observation, should only improve HAC performance.

The Dynamic Earth HAC – a 21st century technology upgrade

A HAC Demonstrator is under construction at the Dynamic Earth earth sciences center in Sudbury, Ontario, Canada. It exploits a pre-existing, elevator shaft that was formerly used to transport visitors to the 'Big Nickel' mine to the sub-surface, and thus the lower part of the unit is installed in the sub-surface and the upper part, accommodating the header/forebay tank and tailrace tank, will stand ~15 m high above the shaft collar level. The general arrangement of the system is presented in Figure 3.

The key design variables of operating head, water flow rate, riser depth (operating pressure), downcomer and riser areas for flow for the HAC Demonstrator were modeled according to Charles Havelock Taylor's compact design for the Peterborough Lift Lock HAC, which was known to have been operated for 60 years. The HAC Demonstrator design for Dynamic Earth deviates from that at the Peterborough Lift Lock in a few aspects: i) the riser duct will not be coaxial with the downcomer to allow access to both sets of pipe work for the full length of the shaft so that instrumentation can be installed; ii) the HAC Demonstrator will be powered by circulating pumps instead of canal water to establish it as an energy efficiency technology; and iii) the HAC Demonstrator will employ an active rather than passive control scheme to modernize and generalize the technology.

HAC Demonstrator Project Objectives

In order to bring about resurgence in adoption of a technology that, according to: i) the published literature, ii) historical operational performance records and iii) pilot scale test work on a ~5m high HAC with ~10 kg/s water mass flow rate, appears economically promising, the following objectives for practical demonstration have been identified.

1. Operational performance, including overall efficiency, should be obtained through direct, prolonged observations on a HAC of commercially meaningful scale, and shown to be consistent with those predicted by modern analytical means, so that design performance of new HACs can be predicted with known levels of confidence and reliability.
2. A HAC of meaningful commercial scale adopting an open-loop and/or a closed-loop flow configuration should demonstrate overall mechanical efficiency consistent with the high levels of those in the historical HAC fleet to prove HACs' potential as energy efficiency technologies that can be applied anywhere, rather than just in proximity to an exploitable watercourse.
3. A HAC of meaningful commercial scale should further be proven to be superior or equivalent to that of modern, industrial scale compressors (e.g. multi-stage, inter- and after-cooled screw or centrifugal compressors). The fundamental comparative will be the overall electrical energy kWh input to the compressor normalized by the kWh of useful pneumatic energy output, and this should be lower for the HAC system than the competing compression technologies in order to prove HACs' potential as an electricity and electrical power conservation technology.
4. A HAC of meaningful commercial scale should have capital, operating and lifecycle costs that compare favorably with those of conventional mechanical compressors. The fundamental comparative will be the discounted cost of compressed air supplied ($/tonne) and this should be lower for the HAC system than the competing compression technologies in order to prove HACs' economic competitiveness.
5. The beneficial effects of 'salting out' and high temperature water circulation on air yield require verification on a HAC system of sufficient scale so that the solution of intake gas is significant and measurable with high confidence without co-solutes being added. With co-solutes added, gas yields and overall mechanical efficiency should return to analytically predicted levels. This will support the adoption of HACs in gas compression applications that extend the operating envelope of the historic HAC fleet (higher pressure applications such as gas liquefaction, gas transmission and industrial refrigeration).

At the time of writing, the construction of a HAC Demonstrator facility is approximately 50% complete, supported by i) Ontario's Independent Electricity System Operator (IESO) through its Conservation Fund, ii) the Northern Ontario Heritage Fund Corporation (NOHFC) through its Northern Innovation Program for Pilot Demonstration and Commercialization Projects, iii) the Ultra Deep Mine Network, through its Energy Reduction program theme and iv) Electrale Innovation Ltd, the commercialization agent in the project. The project aims to achieve the above objectives 1) to 5) in order to prove the efficacy of HACs as energy efficiency technology and to pave the way for their commercial adoption. As HACs are 'large-z' devices (those that require substantial differences in geographical elevation to be available in order to work), the underground mining industry presents a natural fit for an initial adopting Client base. In Ontario, 19 mining operations are connected to the transmission grid, and hence are IESO customers, eligible for the IESO's Industrial Accelerator Program (IAP). The IAP program is designed to facilitate the adoption of energy efficient technologies by large scale, industrial users of electricity in the Province. A key expected outcome of the HAC Demonstrator project is to prove HAC eligibility as a conservation technology so that mining operations consuming electricity and electric power can benefit from them.

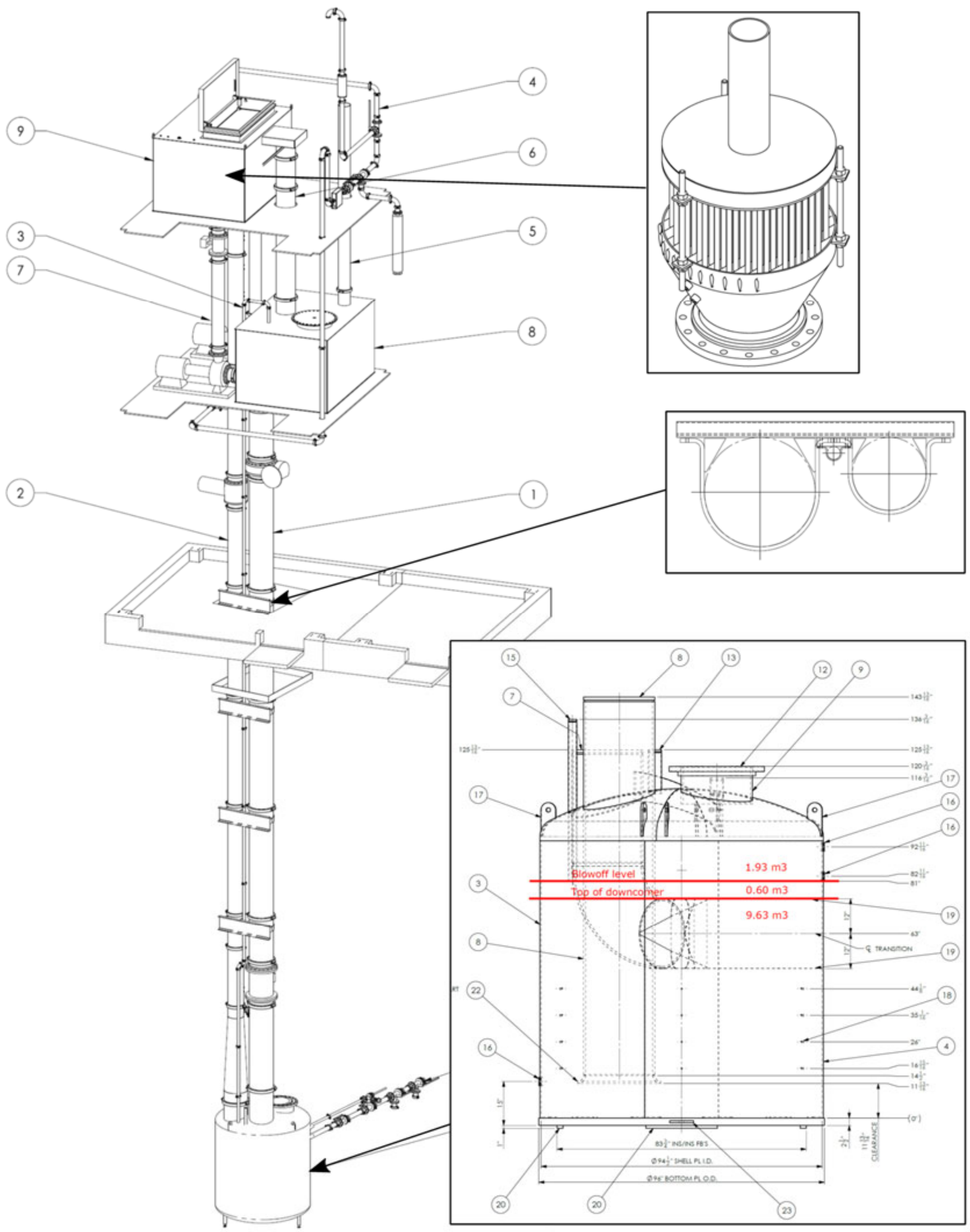

Figure 3. General arrangement of the HAC Demonstrator at Dynamic Earth, Sudbury, Ontario, showing detail of air-water mixing head in forebay tank (9), air-water separator and pipe bracket arrangements. 1– Riser pipe, 2- Downcomer pipe, 3- blow-off pipe, 4– Air intake, 5– tail race surge/vent pipe, 6– Spill-way pipe, 7- pump discharge pipe, 8- tail race tank.

General arrangement of Dynamic Earth HAC

The piping in the shaft comprises a 406 mm (16”) OD downcomer pipe, a 508 mm (24 ”) riser pipe, a 101 mm (4”) compressed air outlet and a 63 mm (2 ½”) emergency pressure relief pipe. All the pipe work has been designed with ANSI Schedule 40 plain carbon steel pipes and 150 class flanges and fittings, and has been butyl lined for corrosion resistance. Pipe work is coupled and connected using Victaulic grooved couplings throughout as these were established to permit sufficient 'give' to accommodate thermal expansion and contraction of the system. The air-water separator has been fabricated in 316L stainless steel, again for resistance to corrosion. Forebay and tailrace tanks are ~9 m^3 in volume, fabricated in carbon steel. Twin ITT / Goulds pumps, model 3180, size 12 x 12 – 14, suited to pumping salt solutions (all iron / 316 SS) at up to 80°C, each with rated power of 13.2 kW (17.7 hp) will together normally circulate 400 kg/s (6300 US gpm) water within the system, facing 5.33m (17.5 ft) head between the water levels in the upper tanks, with rated efficiency of 82.5%. The pump motors are driven by ABB/ITT ACS800 / PS220 variable frequency drives, rated to 24kW each, to afford some process flexibility for the measurement and verification process. A replica of the air-water mixing head used at the Peterborough Lift Lock HAC has been specified, and has been installed within the Header tank.

Measurement and verification instrumentation

Taylor (1913) details an early 20th Century approach to measurement and verification of performance of HACs principally adopting mechanical sensing and mainly for the purposes of billing. Measurement and verification of the HAC Demonstrator performance requires observations of similar quantities but this will be done using modern sensing equipment. Inlet air mass flow is measured by a 4" Krohne Optisonic 7300 ultrasonic volume air flow meter that is accurate to +/-2.0% with +/-0.2% repeatability, supported by i) a differential pressure transducer measuring the pressure difference between atmospheric pressure at the site and the pressure inside the header tank, and ii) a Michell Hygrosmart HS3 temperature and relative humidity (+/-0.8% accuracy, +/-0.2K) sensor installed slightly upstream in the same intake 4" line.

A Krohne Optimass 6400C Coriolis mass flow meter with 0.05% (10:1 turn down from nominal) to 0.1% (20:1 turndown from nominal) 'flat line' accuracy measures the air mass flow rate on the air outlet delivery line. A 'calibration loop' and valving has been installed to place the Coriolis meter and the ultrasonic flow meter in series to improve in-service accuracy of the Optisonic meters, taking advantage of the latter's excellent repeatability. Water mass flow rate is measured by two Krohne Optflux 2000F magnetic flow meters, with accuracy +/- 0.15% installed in twin 12" pump discharge pipes between the tail race tank and the header tank.

3 Krohne Optibar 7060C piezoresistive differential pressure measurement sensors, with reference accuracy of +/- 0.065% for turn down ratio <10, are used to provide redundant observation taking of i) the air gauge pressure in the air-water separator, ii) the air pressure difference between the tailrace tank and the separator tank, and, iii) the gauge pressure (positive or negative) at the header tank. A second Michell Hygrosmart is installed at the outlet of the air water separator so that the psychrometric condition of the air delivered, and its change from the inlet psychrometric condition can be established so that the claims regarding the improved dryness of compressed air in the historical HAC fleet can be tested.

2 Krohne Optisound VU-30 ultrasonic water level sensors, with +/-0.15% (~13 mm) accuracy are installed in the forebay and tailrace tanks. For the air-water separator, a Krohne Optiflex 2200C guided wave radar water level sensor, with +/- 10mm accuracy has been deployed in a stilling well fitted in parallel with the separator so that the indicated water level in the separator can be observed free from frothing or other surface irregularities or motions. This is important because this sensor provides the only signal with which the system is controlled.

In the downcomer, paired, differential temperature sensors, with precision of 5μK, embedded within a Riventa Freeflow thermodynamic pump test system, are used to measure temperature differences to verify the isothermal compression process through direct observation. These difference thermometers are also installed on the suction and delivery sides of the circulating pumps in order that pump efficiency can be estimated (with an accuracy of up to 0.5%) using the Poirson or thermometric method (rather than the, so called, PQ method). The VFDs deliver estimates of torque and rotational speed so that power and pump efficiency can be estimated with them, but ultimately wireless torque sensors are to be bonded to the rotating shafts between pump motor and pump impeller, and well as Hall effect rotational speed sensing, for independent estimates avoiding the use of empirical look up tables stored in the VFDs.

Gas sampling ports are located at ~36 positions around the process pipework, so that the process gas streams may be forwarded to a HIDEN Biostream mass spectrometer gas analyzer equipped with a 40 channel Proteus gas sample line 'multiplexor'. This instrument returns the chemical composition of the gas in sample streams in real time. This instrument permits gas composition observation taking, through direct in-process measurement, to confirm the effect of gas solubility physics on the compression process.

Process control of the Dynamic Earth HAC

The purpose of all this instrumentation is to verify predictions made by the coupled hydrodynamic/gas solubility/psychrometric model of the gas compression process reported by Young (2017), implemented in the MATLAB programming language, so that it may be used to reliably inform design of commercial scale HAC installations. Handling of observations from all instrumentation, including the HIDEN Biostream, has been integrated using TopServer OPC which provides a datalogging/data historian function for all instrument channels, but also serves the Human-Machine-Interface for the machine, as well as process control functionality.

Control of the Dynamic Earth HAC comprises a PID control loop that maintains the water level measured in the separator by varying the position of a 2", electrically actuated, globe air flow control valve (Burket 3361) on the 4" air delivery line. This valve provides independent feedback of its position which is useful for real-time loss-of-signal checking. Compressed air output can be modulated to match user demand by adjusting the set points for independent PID loops controlling the VFD frequency (implemented within the VFD control logic) to the circulating pump motors, and thus the water flow rate; greater inducted air mass flow rates arise as the mass flow of circulating water increases. The pressure of the compressed air produced does not need to be regulated as this is governed solely by the height of the water column in the tail race, although the level of water in the tail race tank is monitored to ensure that vortices do not occur at the suction side pump inlets installed within the tail race tank.

For the HAC Demonstrator, where an extensive experimental program will be executed, all control functionality is implemented in the MATLAB programming language that accesses the system hardware via MATLAB's OPC toolbox. However the separator water level sensor – flow control valve loop will be executed using a microPLC, so that the system control loop may be switched from software to hardware, as appropriate.

Measurement and Verification Strategy

The instrumentation installed on the HAC Demonstrator has been carefully specified so that the following measurement and verification objectives can be verified with levels of significance exceeding 95%.

i) we expect a 40 mK temperature rise in the downcomer. The difference thermometry system that will be installed will return temperature differences with accuracy +/- 0.34 mK. It is expected that the equipment will permit experimental verification, through operational performance measurements, of the isothermal compression process.

ii) We expect to lose approximately 1.5% of the mass of gas to solubility effects as the air is compressed in the downcomer. The mass spectrometer, and ultra high accuracy gas flow metering systems will permit us to verify the model used to make the predictions of expected yield, and whether or not differential solubility of gas species in air is a significant phenomenon. Salt will be dissolved in the circulating water, to defined levels of molality (kg salt / mol H_2O), and predictions of the model will be compared directly with experimental observations. It is expected that the yield of compressed air will increase linearly as the molality of the salt is increased. If it can be shown that dissolution of the co-solute increases the yield of the compressed gas, this opens the way for HACs that can delivery much higher pressures than the historical fleet, and will inform techno-economic assessments of new application areas for HACs such as natural gas compression and air products liquefaction.

iii) The remaining measurement equipment is basically that required to definitively quantify the thermodynamic state of the air and water at inlet, and the air and water at outlet. From these states, the mechanical and overall efficiency of gas compression of the HAC can, in turn, be definitively established from performance observations on large scale equipment.

Overall the measurement and verification strategy is to prove that the model that has been developed to estimate hydrodynamic and solubility / psychrometric performance (for varying aqueous solutions chemistries) of HACs can be relied upon to make predictions, not only the performance of the Dynamic Earth HAC, but the modern-day HACs applied commercially.

Hydraulic Air Compressors may be a disruptive technology

Energy efficiency, power conservation and avoided CO_2

In industrial gas compression contexts, the energy efficiency advantage offered by HACs over conventional air compression systems is set out in detail in Millar (2014), and is predicated on the electricity consumption differences associated with isothermal compression in comparison to polytropic multi-stage compression with inter- and aftercooling. Assuming the baseline comparative is a three stage centrifugal compressor (with intercooling and aftercooling), compressing air to 9 bar then the motor rating of this unit will be ~269 kW / kg/s of air mass flow. This compares to ~234 kW / kg/s of air mass flow for a HAC, a power saving of ~13% for the same provision of compressed air. The electricity saved will depend on the load factor for the system and the demand for compressed air, but if the load factor was unity, ~13% electricity savings would be realized too.

For a 22.6 kg/s scale compressor, total installed motor capacity would be 6080kW and 5260 kW for the centrifugal compressor and the HAC, respectively. With a load factor of unity, electricity savings would amount to 7200 MWh per annum, or CAD 612,000 per annum at an electricity price of CAD85/MWh. In Ontario, where the CO_2 emissions factor is 80 kg $CO_{2,eq}$/MWh_e, the electricity savings would present CO_2 emissions reductions of ~0.58 kT per annum. In Alberta where the grid electricity emissions factor is 820 kg $CO_{2,eq}$/MWh_e, 5.90 kT $CO_{2,eq}$ emissions would be avoided per annum.

Long design life and high reliability

The electricity and CO_2 equivalent savings contribute modestly to the overall cost savings that may be expected with procurement and operation of a HAC. HACs and conventional compressors typically have very different operating lives, or times between major overhauls, Table 1 shows those for HAC installations. Conventional mechanical compressors would require replacement or major overhaul after 10 to 12 years. For HACs, the Ainsworth and Victoria installations had shorter operating lives than other HACs because the mines they were supplying stopped producing and thus demand for air from these systems lapsed before the end of their useful lives.

The simplicity, and consequently, reliability of HACs converts into cost savings through reduced need for personnel for maintenance and operations, and reduced or negligible spare parts costs. For the closed loop or open loop HACs proposed for modern day adoption, the systems may be subject to greater maintenance than the historical systems due to the introduction of circulating pumps and salt service, rather than relying on the head of natural, fresh, watercourses. However the heads faced by the circulating pumps in HAC are low in comparison to their rating. Discussions with pump manufacturers have elicited comments such as: “with that duty, the pumps will last forever.” Outside the HAC system itself, the cooler, drier, oil-free air produced by a HAC in comparison to a conventional compressor will result in reduced cost for mine operators as this quality of air will present fewer problems when supplied to compressed air operated equipment.

Lower lifecycle costs of compressed air supplied: a case study for a replacement 4700 Scfm compressor at a mine

Almasi (2014) demonstrates that the cost of a compressor package from a manufacturer may only be between 17% and 21% of total capital cost (for a 9MW_e rated plant) of the plant supporting that package. In turn, the US DOE (2004) and the UK Carbon Trust (2012) and the both illustrate that capital costs of the compressor plant may be as little as 12% to 20% of the lifecycle costs of provision of compressed air. For comparison with the costs of HACs, the most reliable method of estimating the cost of conventional plants, and the air produced by them, appears to be through adoption of reported accounting costs for established case study situations. Cost estimation must take account of site specific infrastructural circumstances, scale (e.g. motor rating) of the installation, and the cost of energy as a minimum. Consequently, another fairly reliable source of cost information are reports of detailed engineering design studies for compressor installations. For conventional compressor installations in mines, once all the various factors are considered, both the capital and lifecycle costs are high enough to warrant alternative methods of compressed air production, such as a HAC.

In order to expose the collective cost benefits of HACs, a case study calculation follows (Table 2) whereby the life-cycle costs of compressed air supplied to a mining operation are determined through 3 competing scenarios:

A) Construction / major refurbishment and replacement of a mine compressor station with modern, high efficiency, compressors
B) Use of a fleet of diesel fuelled compressors that are rented, with fuel costs borne by the mine operator
C) Construction of a HAC to provide the compressed air

The amount of compressed air to be supplied via these options is 4,700 Scfm, and the delivery pressure is assumed at 9 bar (abs) or 116 psi(g). Figure 4 presents a schematic illustrating key design dimensions, process variables, and construction sequence that may be expected, based on the Ainsworth / Kootenay HAC. The key metric used to measure the economic performance of each option is the discounted (10%) cost of compressed air supplied calculated as: the total annualized costs (annuitized capital expenditure + annual operating and maintenance costs) divided by the annual tonnes of compressed air produced.

Scenario A – Adopt energy efficient screw compressor retrofit

This is the business-as-usual scenario: the default option facing a mine operator when a mine compressor station has reached the end of its effective operating life. The capital expenditure amount of CAD 6.3 million is for a compressor station re-equipping with screw compressors, refurbishment of a cooling tower, and is a professionally produced estimate resulting from a 3rd party engineering feasibility study. The design life of the installation is assumed to be 12 years, and the availability of the machine is 98.6%, based on established maintenance patterns for the compressor system being replaced (5 days per annum). The installed motor capacity is ~1.15 MW, and the load factor for the unit is assumed unity, based on established compressed air demand patterns. 9962 MWh/annum would be consumed by these efficient compression machines. It is assumed, based on current practices at the mine that the machine will require one full-time equivalent employee per shift principally for operations, and that the mine operates 3 shifts. Spares for the compressors are assumed to be 5% of the capital cost of the installation per annum. Discounted cost of compressed air supplied = CAD 27.13 / tonne

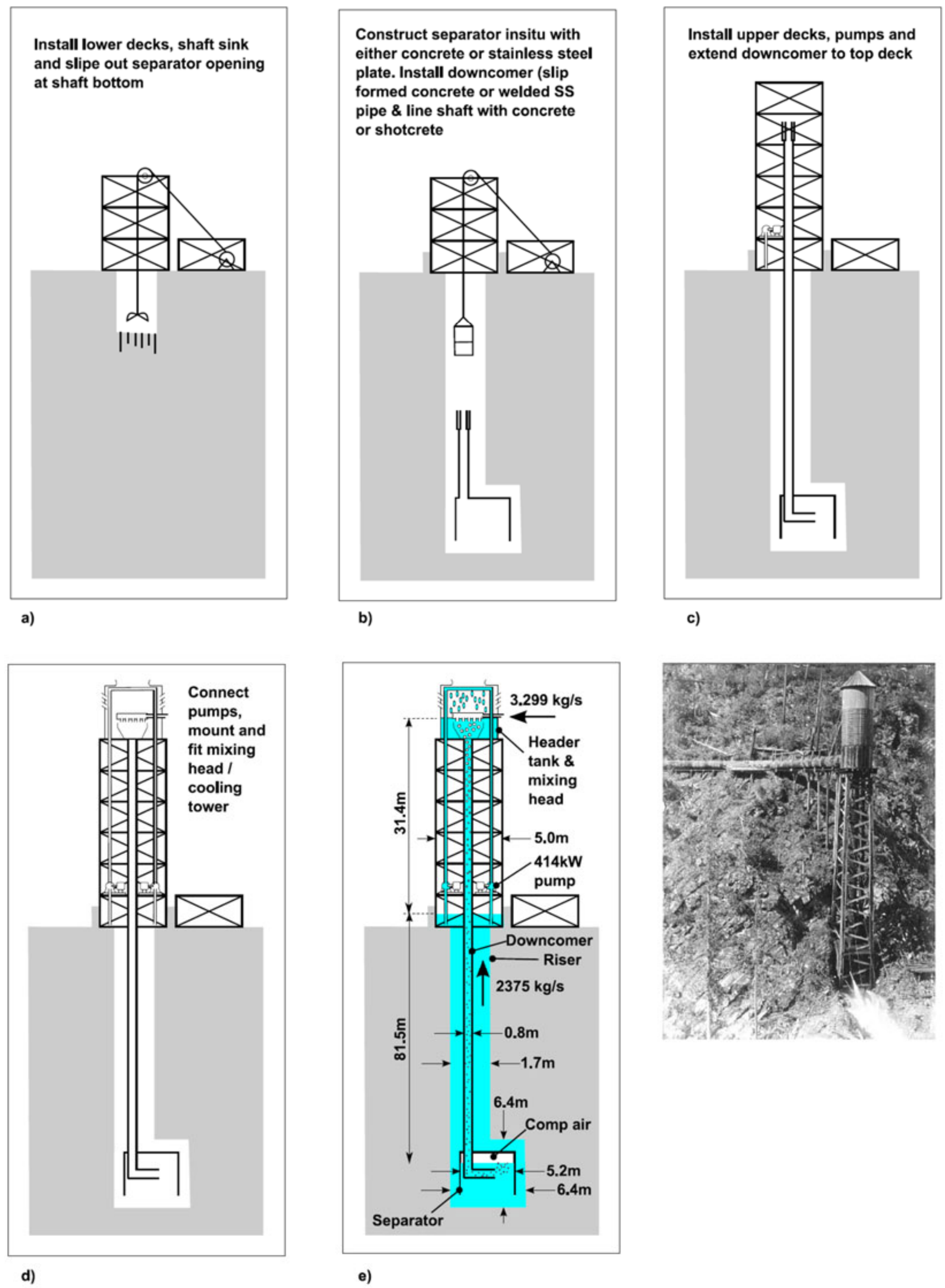

Figure 4. Construction sequence (a to d), process variables and design (e) of a 4700 Scfm HAC based on the Ainsworth / Kootenay installation (lower RHS). Note the design incorporating a cooling tower geometry as part of the header tank

Scenario B – Provide service air with on-hire diesel compressors

This is frequently the situation that occurs when a mining operation can no longer reliably operate its compressor station, but the replacement / overhaul decision has not been taken due to higher priorities in capital budgeting. To deliver the same volume of compressed air, the same feasibility study referred to above also researched diesel compressor rental and fuel costs for this scenario. This scenario does not place any load on the electricity transmission or distribution system, but CO_2 emissions are substantial. There is no capital expenditure to annuitize in this scenario, but rental costs amount to CAD3500 per week, and fuel costs were estimated at CAD 6000 per day. One half FTE employee is assumed attributable to a compressed air cost centre, if only to administrate the contracts with the hire company and the fuel supplier. As the equipment is on-hire, with maintenance and spares assumed integrated into the hire rate at the expense of the hire company, spares costs considered by the mine operator are assumed nil. Discounted cost of compressed air supplied = CAD 27.19 / tonne

Scenario C – Adopt a hydraulic air compressor

A HAC based on the design of the Ainsworth / Kootenay HAC is assumed, and the dimensions, key process variables and construction plan for this option are as provided in Figure 4. The total capital expenditure for the HAC option is estimated at CAD 4.0 million, a figure that has been obtained through consultation with mining industry contractors, and broken out as follows: CAD1.5 million for the tower, CAD 0.5 million for the pumps including electrical connection, CAD 0.1 million for the header tank / cooling tower, CAD 0.3 million pipework and separator vessel construction, and CAD 1.6 million the shaft sink, stabilization and lining to 5.6 x 5.6 metres (~CAD18.4k/metre).

By virtue of the isothermal compression effected by the HAC, in comparison to the polytropic compression stages of the screw compressors, the electricity consumed is taken to be 13% lower for the HAC than the screw compressor option, because the compression ratio is 9. However, following relationships evident between variables in the historical HAC fleet, and allowing for i) solubility loss so that yield is 86% and 2.83 kg/s air is delivered at output rather than ingested at input, ii) pump efficiency of 93% and iii) motor efficiency of 95%, the installed motor capacity expected for this installation can be estimated at ~0.83MW, around 28% lower than the screw compressors. Consequently, the annual electricity savings may actually be substantially higher than assumed in the cost calculation of Table 4. A license fee will be payable by those adopting the patented HAC technology, and this is based on electricity consumption savings against deemed performance of the screw compressors, articulated in the license agreement. This adds a small amount to the overall annual energy costs. The very low maintenance and repair requirements evident in the historical HAC performance record justify negligible spares costs. When equipped with PLC circuits linking the output of a water level sensor in the separator to the actuation of a regulating valve at air delivery, the system may effectively run unattended. Nevertheless, 0.5 FTE employee costs are assigned to the HAC option. Discounted cost of compressed air supplied = CAD 14.54 / tonne

Scenario Comparison

The closeness of the cost of compressed air from Scenario A and Scenario B should not be over-interpreted; their relative values reflect the assumptions made and costs assumed in the professionally conducted feasibility study and it is known that the cost of diesel is volatile. The normal expectation would be that the cost of using diesel compressors would be higher than the costs of owning and operating an electrically driven compressor station, but this will not be the case if there are dramatic falls in the price of fuel, as experienced in 2016. What is striking from the figures is the dramatically lower cost of compressed air from Scenario C, the competing

HAC option, and this can be seen to be principally attributable to lower employment, spares and maintenance costs.

Table 2. HAC value proposition for a mining client replacing an existing compressor station at a mine

Scenario	Adopt an energy efficient screw compressor retrofit		Provide service air with on-hire diesel compressors		HAC, Ainsworth / Kooenay CAPEX	
CAPEX (installed, 2015)	$M	6.3	Rental cost		$M	4.0
Discount rate		10%	($/week)	3500		10%
Life between major overhauls	years	12	Annual rental		years	20
Annuitized CAPEX	$M/yr	0.92	($M/yr)	0.182	$M/yr	0.47
Operating hours of plant	h/yr	8640	h/yr	8640	h/yr	8640
Mass throughput	kg/s	2.83	kg/s	2.83	kg/s	2.83
Standard air density	kg/m3	1.27	kg/m3	1.27	kg/m3	1.27
Volume throughout	Sm3/s	2.22	Sm3/s	2.22	Sm3/s	2.22
	Scfm	4700	Scfm	4700	Scfm	4700
Annual air compressed	MTPA	0.09	MTPA	0.09	MTPA	0.09
Energy consumed	MWh/yr	9962	Diesel cost ($/day)	6000	MWh/yr	8667
Price of electricity	$/MWh	85			$/MWh	85
Annual energy costs	$M/yr	0.85	$M/yr	2.16		0.74
Licence fee @ 20.0% savings	$M/yr	0	$M/yr	0	$M/yr	0.02
Annual energy costs	$M/yr	0.85	$M/yr	2.16	$M/yr	0.76
No. of employees		3		0.5		0.5
Average employment cost	$/yr	100000	$/yr	100000	$/yr	100000
Annual employment cost	$M/yr	0.30	$M/yr	0.05	$M/yr	0.05
Spares, ex. O/H items (%CAPEX)		5%		0%		0%
Annual spares cost	$M/yr	0.32	$M/yr	0.00	$M/yr	0.00
Summary	$M/yr	%	$M/yr	%	$M/yr	%
Annuitized CAPEX	0.92	38.7	0.18	7.6	0.47	36.7
Energy costs	0.85	35.5	2.16	90.3	0.74	57.6
Licence fee					0.02	1.7
Employment costs	0.30	12.6	0.05	2.1	0.05	3.9
Spares costs	0.32	13.2	0.00	0.0	0.00	0.0
Total annualized cost	2.39	100.0	2.39	100.0	1.28	100.0
Discounted cost of compressed air supplied	**($/tonne)**	**27.13**	**($/tonne)**	**27.19**	**($/tonne)**	**14.54**

Summary

This paper has outlined the performance of historical HAC installations. These were renewable hydropower to pneumatic power conversion installations that operated with high thermodynamic efficiency but suffered from diminished yield due to solution of pressurized gas that lowered the overall efficiency of the devices. Another deficiency of the historical technology was that HAC were limited in application to situations of geographical co-occurrence of hydropower resources and demand for pneumatic power. These deficiencies are priorities addressed in the HAC Demonstrator project, which implements the HAC concept in either closed loop or open loop configuration, and overcomes the two principal deficiencies of the historic installations. A closed or open loop concept allows the concept to be applied anywhere and permits the use of co-solutes to be added to the circulating water to reduce solubility loss. An illustrative example calculation permitting the comparison of the discounted cost of compressed air supplied from i) a compressor station utilizing screw compressors, ii) 'on-hire' diesel fuelled compressor fleet, and iii) a HAC following the design of the Ainsworth HAC, suggests that in a modern context, closed loop or open loop HACs may become a disruptive energy efficiency technology in the domain of stationary industrial scale compressors.

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