PROCEEDINGS OF ECOS 2015 - THE 28TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
JUNE 30-JULY 3, 2015, PAU, FRANCE

Conceptual design of a modern-day hydraulic air compressor

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Abstract:

Hydraulic air compressors (HACs) operating in the early 1900s used natural water flows to compress air near isothermally. The conceptual design of a modern-day demonstration scale HAC described in this paper is primarily based on the 1906 Peterborough Lift-Lock installation in Ontario but has been modified to meet scientific demonstration objectives. These are: i) to develop and validate hydrodynamic models of the HAC incorporating psychrometric and solubility phenomena, ii) to demonstrate the energy efficiency credentials of these systems, iii) to explore the application of compressed air as a cooling medium for deep mines, and iv) to explore HAC potential for carbon capture systems. An important distinction from historical HAC installations is that the water reticulates in the system described in the current work. The benefit of a practical isothermal compression is retained while opportunity is offered to modify gas solubility behaviour through adoption of co-solutes and manipulation of the circulating water temperature. These aspects presented new challenges for HACs that were addressed as part of the design effort. The general arrangements for pipe work had to consider the potential for appreciable thermal strain and enhanced potential for corrosion. Open and closed loop systems required that special attention be given to pump and HAC performance matching. The level of instrumentation planned for the demonstration scale installation is by necessity extensive because of a need to obtain certification for HACs as an energy efficiency technology. A pilot scale HAC is operational and is being used to inform a functional description of operation of such systems, which in general is not well reported in the literature, and also to guide control system design.

Keywords:

Compressed air, Hydraulic air compressor, Isothermal compression, Two phase flow.

1. Introduction

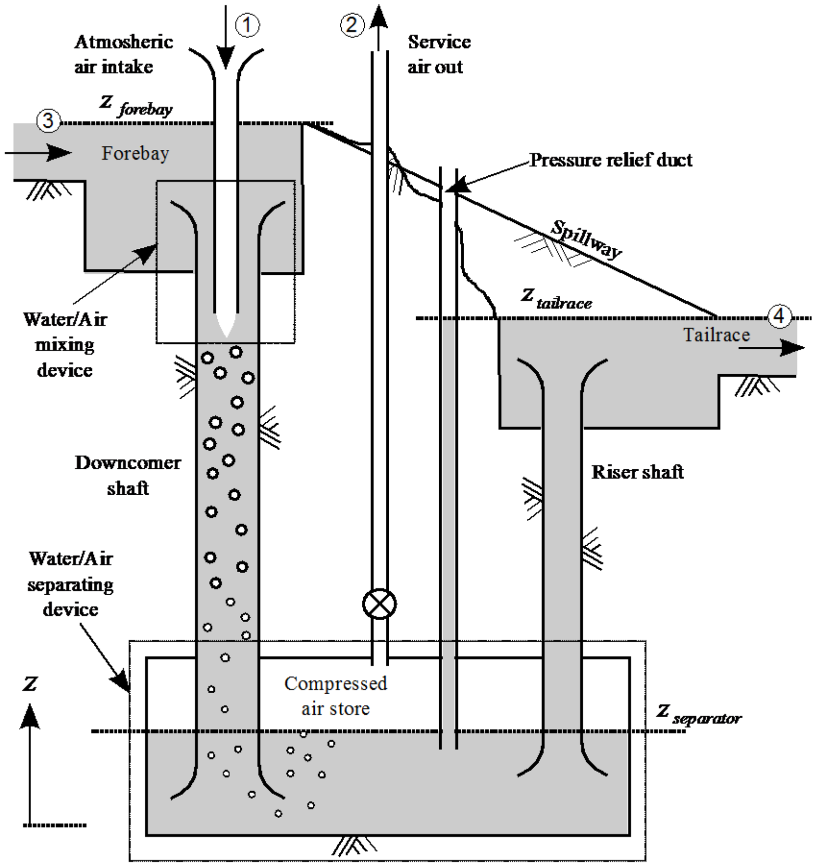

Fig. 1. Schematic of a traditional hydraulic air compressor.

A hydraulic air compressor (HAC) is a device that uses the downward flow of water to induct air into the water stream and compress it [1]. Historically, HACs operated using water from natural watercourses and a traditional HAC is shown schematically in Fig. 1. The water enters the system from the natural watercourse at position 3 and is collected in the forebay. Water acting as the motive, or primary, fluid of a water/air mixing device (rather like a jet pump) induces air entering at position 1 via a venturi effect. At typical water:air mass flow rate ratios (between 500:1 and 2000:1), the two phase, dispersed bubbly flow passes down the downcomer shaft [1]. The potential energy, principally of the liquid (water) phase is converted to pressure energy, and this pressure is transmitted to the air. The heat that is generated from the compression of the air is simultaneously transferred from the air to the water. Since the water has a much higher mass flow rate and heat capacity, the measurable temperature rise in the air is small. The air-water mixture flows to a separating device, where the compressed air is collected and delivered where required (position 2), while the water continues to the riser shaft and rejoins the watercourse (position 4). This system has two key dimensions: i) the head required to drive the system which is given by the difference in elevation between the water levels in the forebay and the tailrace, and ii) the delivery pressure of the system which is given by the difference in elevation between the water levels in the separating device and the tailrace.

1.1. HAC History

The HAC technology was developed by Charles Taylor who built the first HAC in Magog, Quebec in 1896 [2]. This led to the installation of 17 other HACs around the world, including locations in Canada, the United States, Sweden, Germany and Nigeria [1]. The largest HAC was the Ragged Chutes installation in Cobalt, Ontario, Canada. The Ragged Chutes installation diverted water from the Montreal River to twin concrete-lined downcomer shafts, each 2.6 m (8.5 ft) finished diameter, used a 283 m (927 ft) long air separation chamber that was 6.1 m (20 ft) wide and 7.9 m (26 ft) high and a 6.7 m diameter riser shaft. The free air delivery (FAD) of Ragged Chutes was 22.3 kg/s (18.9 Sm^3/s or 40,000 Scfm) and its delivery pressure was at 822 kPa gauge (120 psig), serving silver mines in the area [2].

The other HAC installations most relevant to the current project are the Peterborough Lift Lock in Ontario (drawing in Fig. A.1) and the Clausthal compressor in Germany. The Peterborough Lift Lock

HAC featured a single shaft design using a cyclone separator with the water outlet exiting the base of the cyclone and the riser ‘duct’ occupying the annular region around the pipe work. Because of its relatively compact design, the Peterborough Lift Lock HAC was chosen as a model for the conceptual design of the large scale demonstrator of the current work. The Clausthal compressor was installed in an existing mine shaft and featured an in-line water-air mixing head (shown in Fig. 5), two aspects that feature in the design presented here. Historically, these installations are reported [2] to have efficiencies ranging from 70 to 80 per cent but these efficiencies did not properly take into account the effect of gas solubility [1]. Nonetheless, these installations were very reliable. Ragged Chutes operated near continuously for 70 years with only two interruptions for maintenance [1]. While HACs had such considerable benefits, the technology met its demise due to: i) electricity being a more marketable form of renewable energy than compressed air, ii) the differential solubility of oxygen and nitrogen in water, which led to oxygen depletion in mine ventilation air, and iii) increased maintenance costs of the compressed air distribution system. However, in the modern mining context, these limitations are either no longer relevant or are easily mitigated [1].

1.2. Objectives of the HAC Demonstrator Project

HACs are interesting as a modern, industrial scale energy efficiency technology, because they offer a practical means of delivering isothermal, minimum work, gas compression; the potential commercial applications of a minimum work compressor are manifold. For the demonstration project reported herein, it is the cooling of ventilation air in ultra deep mines (>2,500 m depth) which motivates the work. This paper reports on an installation to support a three year long research initiative, currently in the middle of the first year of the programme, which has both scientific and commercial objectives. Its commercial objective is to obtain enough industry support to develop a commercial scale, modern-day HAC.

In the mine air cooling context, Table 1 summarises calculations that show that a HAC of a similar scale to Ragged Chutes may be expected to depress the temperature of 800 m^3/s (941 kg/s) mine air entering production workings at a depth of 2,800 metres by 3.4°C. This is sufficient to permit the mine to deepen by 6 to 10 working levels, for a mine producing at a rate of ~3,500 tonnes of ore per day, which may extend its working life by a decade or two. Table 1 assumes that circulation pumps are used to return water from a ‘tailrace tank’ to a ‘forebay tank’ rather than relying on the opportunistic presence of a natural watercourse. The implied method of provision of cooling is compression of (dry) air by the HAC, delivery of compressed air to working level in pipe work and expansion of the compressed air through a turbo-expander with isentropic efficiency ~90 per cent coupled to a generating set. For a Ragged Chutes scale installation, in addition to producing electricity, the turbo-expander will exhaust 22.3 kg/s air at -98.7°C, which is intended to be the principal product of the turbo-compressor. This air stream will cool the mine ventilation air, at 47.4°C by the time it enters the production level workings due to adiabatic (auto-)compression as it descends the shaft, to 44.0°C, by means of direct contact mixing.

For a given water circulation rate, the HAC geometry (duct diameters and lengths) governs the ratio of water to air mass flow rate (i.e. the free air delivery), the head available to drive the system and the compressed air delivery pressure. Thereafter the temperature of the let down air, and the overall coefficient of performance of the refrigeration system (of 1.96) are dictated by the turbo-compressor performance and the depth of the mine workings (as the turbo-compressor must work against the elevated air pressures experienced at depth).

The 84 m depth (separation level to tailrace level) of the Ragged Chutes HAC installation represents a current practical limit of depth; beyond it, pressure-related gas solubility behaviour becomes significant, and the loss of compressed air due to solution in the water becomes appreciable [1]. As this solubility behaviour is now well understood, and the HAC concept herein involves *circulating* water, it is conceivable that the gas solubility behaviour can be controlled through use of a co-solute. As reported in [1], circulating a 1 molar solution of sodium sulphate instead of water may reduce gas solubility by half, permitting the depth of HAC installation to double and the pressure of air delivered by the HAC to increase correspondingly. Table 1 shows a Ragged Chutes scale HAC installation with a depth of 184 m, a delivery pressure of 1801 kPa gauge and a coefficient of performance of 2.9, with only a modest increase in driving head required to overcome increased downcomer wall friction and bubble drag. Table 1 also shows predicted performance of two smaller HAC installations, one corresponding to the laboratory scale HAC constructed to support investigations and one at the proposed demonstration project scale, which will produce air streams of -2.5°C and -54.7°C respectively, if similarly used to drive a turbo expander with an isentropic efficiency of 90 per cent.

Table 1: Projections of HAC & turbo expander performance for HACs of varying scale

Defining variables	Units	Laboratory scale HAC	Demonstrator scale HAC	Ragged Chutes scale HAC	Ragged Chutes scale HAC + solubility 'fix'
Atmospheric pressure	(kPa)	99	99	99	99
Atmospheric temperature	(^{o}C)	25	25	20	20
Depth of mine	(m)	0	0	2800	2800
Diameter of shaft	(m)	0	0	8	8
Ventilation requirement at shaft collar	(m^3/s)	0	0	800	800
Water temperature	(^{o}C)	15	15	10	10
Depth between tailrace and sep device	(m)	2.800	20.00	83.97	183.97
Driving head	(m)	1.187	5.00	15.09	16.00
HAC compressed air delivery	(kg/s)	0.00296	0.135	22.3	22.3
Mass flowrate water : Mass flowrate air		3343	2964	1015	1015
Pump efficiency	(%)	90	90	90	90
Pump motor efficiency	(%)	95	95	95	95
Isentropic efficiency of turbo expander	(%)	90	90	90	90
Turboexpander generator efficiency	(%)	95	95	95	95
Predicted variables					
Gauge pressure of compressed air produced	(kPa)	27.4	195.8	822.0	1800.9
Temperature of air leaving turboexpander on surface	(^{o}C)	-2.5	-54.7	-111.0	-136.9
Pressure of ventilation air at production level	(kPa)	0	0	134	134
Temperature of ventilation air at production level	(^{o}C)	0	0	47.4	47.4
Temperature of air from turboexpander at production level	(^{o}C)	0	0	-98.7	-127.0
Degrees of cooling of ventilation air	(^{o}C)	0	0	3.4	4.0
Electric power consumed by HAC circulation pump	(kW)	0.135	22.9	3922.6	4159.8
Electric power produced by turboexpander generator	(kW)	0.049	8.9	2281.8	2837.5
Cooling power to ventilation air by direct contact mixing	(kW)	0	0.0	3211.2	3836.3
COP of HAC + Turboexpander		0	0	1.96	2.90

The scientific objectives of the HAC Demonstrator project are thus:

1. to develop and validate the hydrodynamic models for HACs that include gas solubility and psychrometric aspects, at large scale;
2. to demonstrate HACs as industrial scale, energy efficient compressed air producers;
3. to explore the application of compressed air as a cooling medium for deep underground mines; and
4. to explore the use of HACs in carbon capture systems.

The carbon capture applications are longer term goals of the project and are not discussed in this paper.

2. Conceptual Design of a Large Scale HAC

A 3D model of the HAC Demonstrator conceptual design is shown in Fig. 2. It is expected to produce 0.135 kg/s of dry air at 196 kPa gauge with a water circulation rate of 0.4 m^3/s.

The HAC designed in the conceptual stage is equipped to perform the following tasks: i) to test methods of reducing the gas solubility in the circulating water (by increasing process water temperature to 80°C and by use of a co-solute to the gases); ii) to test various air/water mixing heads; iii) to test a closed loop configuration (eliminating forebay tanks, installing in-line mixer); iv) to establish the efficiency of the machine to achieve energy efficiency technology certification from the Ontario Power Authority (OPA); and v) to monitor and control the process using a SCADA and PLC system. The constructability, maintainability of the installation, and the safety of workers was prioritized throughout the conceptual design process.

2.1. Design Overview

The HAC Demonstrator will be built at Dynamic Earth, an earth sciences centre in Sudbury, Ontario. It will be housed in the former elevator shaft that brought visitors to Dynamic Earth's underground exhibit. This installation site provides two main benefits: i) the capital to sink a shaft is not required, and ii) access to the bottom of the HAC is available through the underground exhibit.

The HAC Demonstrator was modelled after the compact design of the Peterborough Lift Lock HAC, which operated for 60 years. However, the conceptual design deviates from 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 modernise the technology.

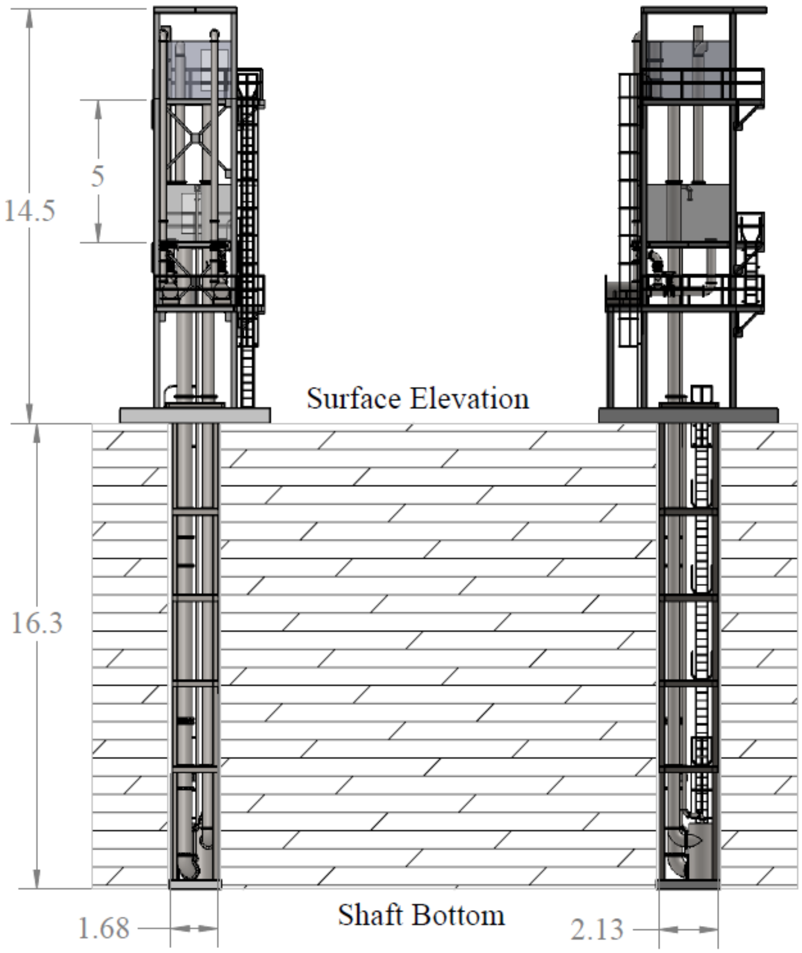

Fig. 2. Side view (left) and front view (right) of the conceptual design. Dimensions are in metres.

The conceptual design can be broken down into: the shaft infrastructure, the steel superstructure, the pump circuit, and process control and instrumentation. These will be considered in further detail in the following sections.

2.1.1. Shaft Infrastructure

In order to properly size the metalwork inside the shaft, drawings for the dismantled elevator that previously occupied the shaft were retrieved from the Ontario Technical Standards and Safety Authority (TSSA). The drawings indicated that the metalwork for the elevator fit in a 2.13 m by 1.68 m (5.5 ft by 7 ft) area. The shaft infrastructure, including the piping, the high pressure cyclone (HPC) separator, and the ladder way was thus designed to fit inside this envelope.

The piping in the shaft will comprise a 0.406 m (16 inch) downcomer pipe, a 0.508 m (20 inch) riser pipe, a 0.101 m (4 inch) compressed air outlet and a 0.063 m (2 ½ inch) emergency pressure relief pipe. All the pipe work was designed with schedule 40 plain carbon steel pipes and 150 class flanges and fittings.

The HPC air-water separator is expected to be 0.914 m (36 inch) in diameter and 2 m tall (Fig. 3). The two phase flow enters the cyclone through the downcomer inlet. Within the cyclone, a vortex flow drives the air and water separation. Compressed air from the core of the vortex exits the separator through an axial outlet and the water exits via a tangential outlet to the riser duct.

A ladder way will run along the full height of the shaft to allow access for installation and maintenance of pressure and temperature instruments and gas samplers. Welded wire mesh brattice panels will be installed around the outside of the ladder way for worker safety in the shaft. Platforms will be installed at 3 m intervals with the ladders offset to minimise the maximum fall distance.

As the HAC Demonstrator is planned to be subjected to thermal cycling as a means to control gas solubility, thermal expansion of the pipe work became a major concern. When experiments with 80°C water are being conducted, the largest deformation expected in the pipe work would be 0.250 m. Initially, the design featured spring suspension, at the collar, for the shaft infrastructure and forebay and riser tanks, in order to accommodate the strain. Subsequent work has identified a simpler solution in the use of 'Victaulic' pipe couplings.

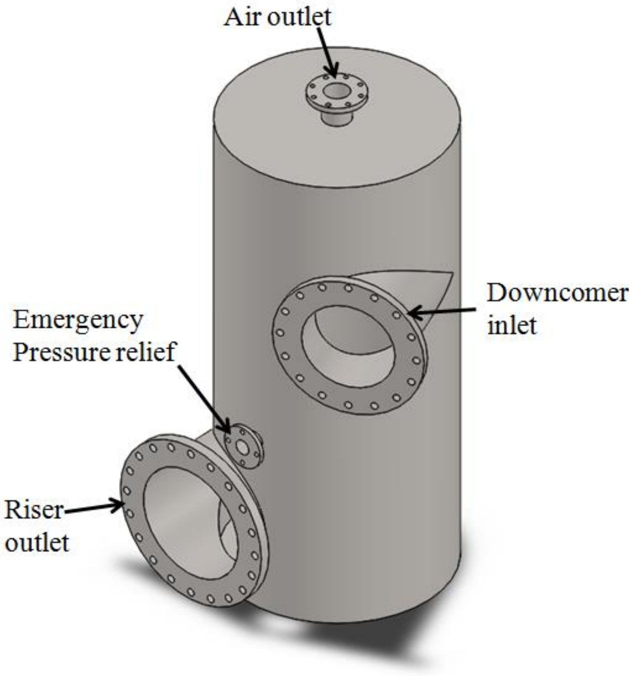

Fig. 3. 3D model of the high pressure cyclone (HPC) separator.

2.1.2. HAC Superstructure

The forebay tank will receive the water discharge from the pumps and will house the air/water mixing head. It will also have a bulkhead door to provide access to the pipe work and the air/water mixing head for manipulation during experimentation. The tailrace tank will receive the water flow from the riser pipe, and feed the centrifugal pumps. It will also allow for the gas coming out of solution as the water depressurizes in the riser pipe to separate from the water and vent out the surge pipe. This will ensure that no air bubbles are present when the water passes through the pumps. The downcomer pipe must be vertical to inhibit coalescence and separation of entrained air bubbles, so it will pass through the tailrace tank. The forebay and tailrace tanks will be 3 m long, 3 m wide and 2 m tall and spring mounted to the frame to allow for thermal expansion of the pipe work. The tanks will require a large footprint to reduce the transience in the water levels developed by water flow rates of 0.325 to 0.700 m^3/s.

The superstructure will feature ladders and gantries to access both water tanks and the pump mezzanine. The pump mezzanine permits self-priming pump installation, which is important when the intention of the installation is for it to be drained fairly frequently for experimental purposes, even if the final intent is for it to be drained only during (rather infrequent) maintenance periods. Two crane monorails will be placed on the superstructure: one underneath the pump mezzanine to lift equipment from inside the shaft and the second at the top of the structure to bring items to either tank or the pump mezzanine. A surge pipe leading from the tailrace tank will protect against sudden changes in water level in the tailrace tank. During the filling process, this surge pipe will also act as a vent pipe to prevent air being trapped in the tailrace tank and to allow the water levels in the system to reach the forebay tank. A spillway pipe will connect the forebay and tailrace tanks to permit any excess water delivered to the forebay tank to flow back to the tailrace tank, bypassing the compression circuit.

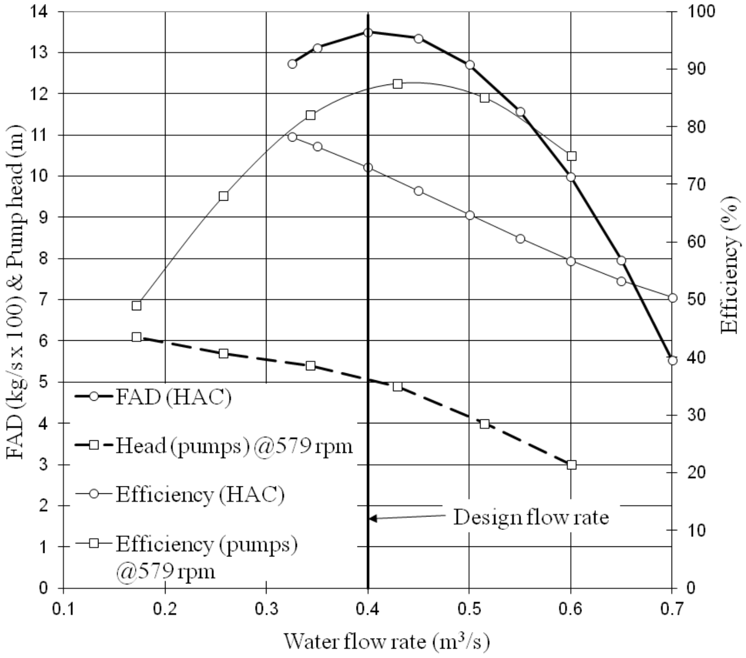

Fig. 4. HAC Demonstrator project installation compressor and pump design curves.

2.1.3. Pump Circuit

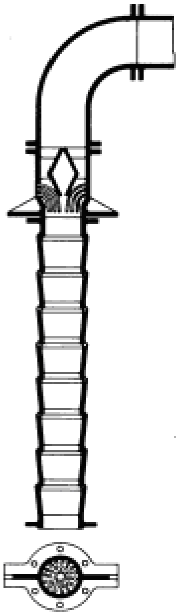

Fig. 5. The Clausthal HAC air water mixing arrangement. Source: Schulze [2]

The pump circuit's function in the open loop configuration will be to circulate the water from the tailrace tank to the forebay tank. There will be two end suction centrifugal pumps that will handle between 0.170 to 0.350 m^3/s of water each, controlled by adjusting the motor speed through a variable frequency drive (VFD). Pump selection has taken careful account of HAC performance for a maximum FAD condition that will occur with a water flow rate of 0.400 m^3/s (Fig. 4) with the pumps and the HAC both working at close to maximum predicted efficiency. This is preferred over a throttling valve system that would introduce loss into the fluid circuit and so may challenge energy efficiency certification. The pumps will have isolation valves and system bypasses as a safety and maintenance precaution. The pumps will be equipped with ultra high precision temperature probes and pressure instruments to permit high precision determination of pump efficiency using thermometric methods.

The discharge pipes will merge in a wye manifold to combine the two flows during a transition to a pipe diameter of 0.406 m (16 inch) OD and discharge into the forebay tank onto a baffle plate directly above the downcomer pipe. For the open loop operation, the baffle plate will divert flow away from the downcomer pipe inlet to minimise disruption to the air/water mixing process. The positioning of this inlet was designed to allow for the transition to closed loop operation, in which case pipe spools will be used to connect the pump discharge to the downcomer duct and an in-pipe air/water mixing head similar to the one used at the Clausthal HAC installation will be installed (Fig. 5). In the closed loop configuration, the head to drive the compression system and circulate the water will be provided by the pumps. Thus, on the pump mezzanine level, the pipe work and valves arrangement permit running the pumps in series as well as parallel, to investigate enhancement of the HAC performance by these means.

2.1.4. Process Control and Instrumentation

The Process and Instrumentation Diagram (P&ID) prepared as part of the conceptual design is shown in Fig. 6. The instrumentation and controls required to maintain the safe operation of the HAC Demonstrator and to validate the theoretical model are: flow, pressure, temperature, level and input power measurements, flow controls and a mass spectrometer.

Flow meters will be located on the air inlet, air outlet, downcomer pipe, riser pipe and pump discharges. The flow meters on the air inlet and outlet (FT1 and FT3) will perform a mass balance of the air. Similarly, the flow meters on the pump discharges and the riser pipe (FT4, FT5 and FT6) will measure the mass flow of water going through the system. The flow meter on the downcomer pipe (FT2) is experimental and will be used to evaluate whether or not it is possible to measure a two-phase flow directly.

The pressure measurements will include a barometer (PT1) and two differential pressure sensors to measure the air gauge pressure entering and exiting the system (DPT1 & DPT2). In addition to those shown on the P&ID, there will be pressure sensors at regular intervals on the downcomer and riser pipes to help characterise the thermodynamic properties of the fluids throughout the process as well as to determine the pressure of the fluids entering the gas samplers leading to the mass spectrometer.

The temperature and relative humidity measurements (TT&RH 1 & 2) will be necessary to characterise the psychrometric properties of the air entering and leaving the system. As with the pressure sensors, there will be corresponding temperature sensors at regular intervals along both the downcomer and riser pipes near each of the mass spectrometer sampling points.

Three level sensors are specified in the system: one in the forebay tank (LT1), one in the tailrace tank (LT2), and one in the HPC (LT3). These will monitor the head delivered to the system in the open loop configuration (using LT1 and LT2) as well as the water levels during the filling process. It is expected that LT3 will not provide meaningful results for control purposes due to the steep vortex surface that forms inside the cyclone during operation, but it will still be used for monitoring during filling and draining procedures. A difference of head calculated by subtracting the pressure measured at DPT2 from the head identified by LT2 in the tailrace tank will estimate the water level in the cyclone.

As is evident in Fig. 6, there are a large number of valves required for the HAC Demonstrator. The valves that will be pertinent for the control of the system are the motorised valves (MV1 & 2). MV1 will be the pressure control for the air delivery and will provide a load on the system to regulate the water level inside the HPC. If MV1 leaks or fails, the instruments below the valve will be inundated with water. MV2 will regulate the amount of air entering the system. The FIC is a flow control valve that will regulate the flow of air released to atmosphere. V11 is a gate valve that will be used to change the pump configuration from parallel to series if more head is required in the closed loop HAC. All other indicated valves will serve to isolate or drain components of the system.

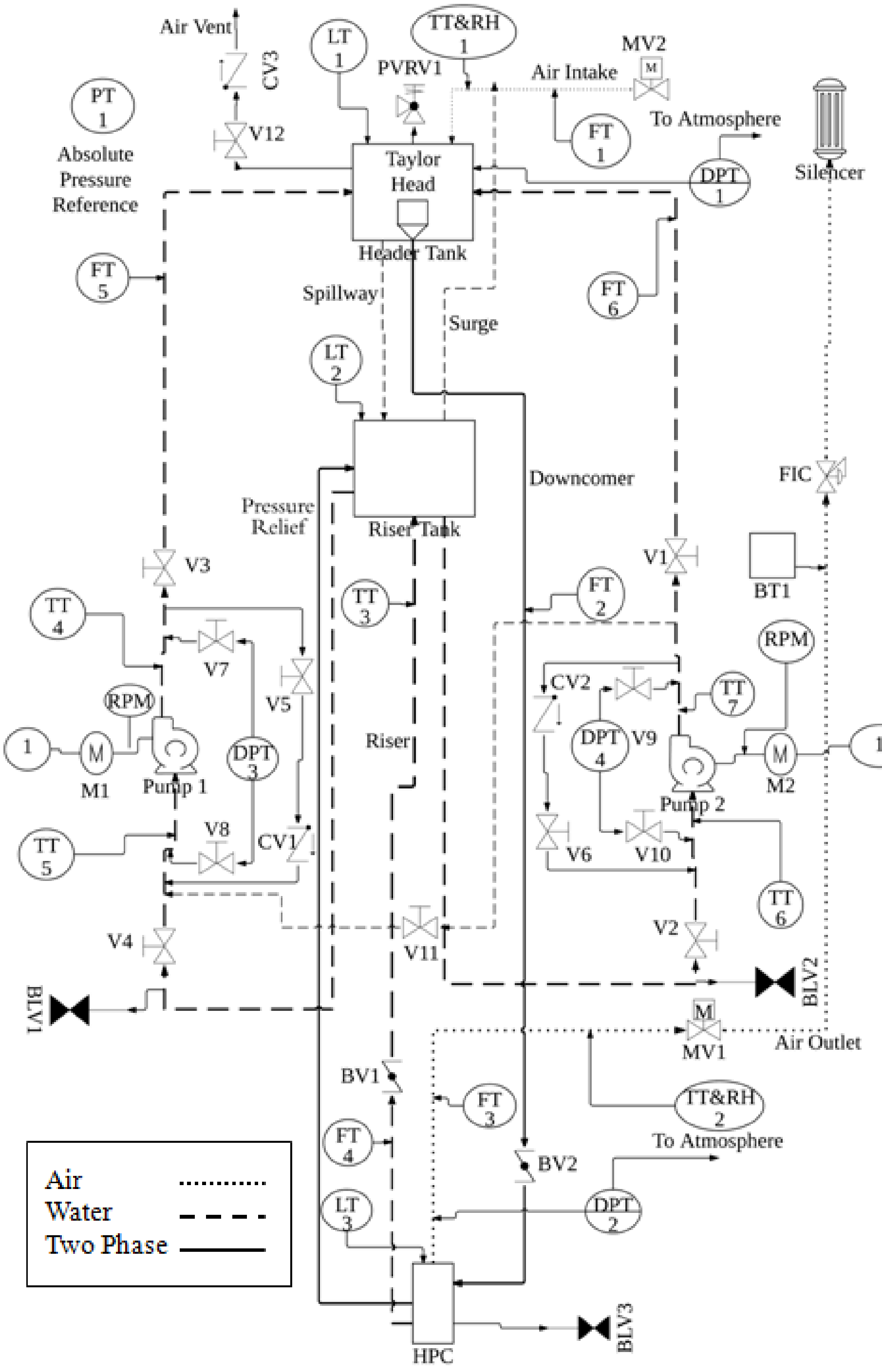

Fig. 6. HAC Demonstrator process and instrumentation diagram showing air, water & two phase flows.

Additionally, torque and speed sensors will be placed on the shaft of the pump (shown as RPM in Fig. 6) and power input sensors (not shown in Fig. 6) will be placed on the input power before the VFD of the pumps. These sensors will measure the mechanical input power to the system. The mass spectrometer will analyse the gas both in and out of solution to fully characterize the solubility kinetics. All instruments and motorised valves will be integrated with a SCADA and PLC control system. These systems will ensure the safe operation of the HAC as well as collect all the necessary data.

2.1.5. Corrosion and materials selection

Since the corrosion rate of carbon steel in contact with water and aqueous solutions is affected by factors such as pH, dissolved oxygen, temperature, dissolved salts and water velocity [3], the issue of potential corrosion of the carbon steel pipes was investigated. The amount of dissolved oxygen in the water increases with partial pressure of oxygen and water/gas surface area, and decreases with increased salt concentration and temperature. The higher the dissolved oxygen concentration and the higher the speed that dissolved oxygen can reach the metal surface, the higher the corrosion rate. Carbon dioxide (CO_2) dissolved in water forms carbonic acid (H_2CO_3), which lowers the pH and increases corrosion rates. When salts such as sodium chloride (NaCl) and sodium sulphate (Na_2SO_4) are dissolved in water, the corrosion rates are initially increased, due to higher conductivity. However, when the concentration of dissolved NaCl becomes higher than ~0.5 mol/L of solution the corrosion rates decrease, due to the decreased solubility of oxygen [3]. In the case of Na_2SO_4, this critical concentration is reported to be 0.1 mol/L of solution [4]. Elevated temperatures initially cause higher corrosion rates, due to higher reaction kinetics, but higher temperatures mean decreased oxygen solubility and so, above 80ºC, corrosion rates decrease [3]. Increased water velocity accelerates corrosion, as it increases the speed by which dissolved oxygen is supplied to the metal surface. In fresh waters, this happens up to a critical velocity of ~0.3-0.7 m/s, after which, the corrosion rate decreases because oxygen is transported to the surface at a speed higher than the speed it is consumed [5]. In sea waters, because of high concentration of Cl^-, the corrosion still increases above the critical velocity but at a lower rate. When water reaches very high velocities (~20 m/s), erosion-corrosion comes into effect, where the protective iron oxides surface films are removed and bare metal is been exposed to corrosive environment [5]. Suspended solids in the water and two phase flows can create especially serious attacks. Erosion-corrosion is accelerated where there are changes of flow, direction and increased turbulence, such as at elbows, tube constrictions, turbines and pumps.

In the HAC pipe work, most of the parameters described above are present and affect the expected corrosion rate. A two phase fast moving flow of water and air, with increasing liquid/gas pressure and therefore oxygen solubility, will be present in the down comer pipe and gas separator. When changes in temperature and dissolved solutes, such as salts and other gases, are introduced into the system, all the right ingredients will be there for the “perfect storm” of active corrosion to develop.

Consequently, the use of pipes made from thermoplastic materials, such as High Density Polyethylene (HDPE) or Chlorinated Polyvinyl Chloride (CPVC), or thermoset materials such as Glass Reinforced Polyester (GRP) was considered, but the potential loss of strength and thermal strain at elevated temperatures meant that they were inappropriate. Rubber lined carbon steel was assessed but the cost of this selection was high. The best option found to date is carbon steel pipe spray coated with erosion-corrosion resistant polymer alloy, designed to operate at temperatures up to 95 °C [6].

3. Laboratory Scale HAC

The functional description and operating parameters are being determined on a laboratory scale HAC (Fig. 7), with the goal of informing the conceptual and detailed design, operation and instrumentation of the demonstrator scale unit. At this time, the prototype is mechanically operational. It is constructed almost entirely of clear PVC so the process is visible during operation, a key feature for research purposes that will not be possible in the large scale demonstrator. The pilot scale HAC is 5 m high with 1.2 m of head and nominally delivers 0.00296 kg/s of compressed air at a delivery pressure of 27.4 kPa gauge with water flow rate of 0.0099 m^3/s (Table 1).

The rigidity of the pipe work structure in the pilot scale HAC led to failure of the flanges on the downcomer pipe when the separator tank was being filled with water. The weight of the water in the separator tank put the pipe work into tension and cracked the brittle welds in the downcomer pipe. This was a strain failure similar to that expected from the thermal expansion of the pipe work in the large scale demonstrator, without design precaution. An instrumentation and control regime will be applied to the laboratory scale HAC to help validate the hydrodynamic model that predicts the operating points, air yields and thermodynamic efficiency of the machine. The first instrumented tests on the laboratory scale HAC began in February 2015.

4. The Next Steps

With the conceptual design complete, an engineering group at Cementation Canada Inc. has entered into a detailed design phase. The detailed design will review the conceptual design for building code and technical standards compliance and produce detailed drawings signed by a professional engineer. These drawings will be used to apply for building permits with the City of Greater Sudbury, Ontario and will also be provided to contractors and fabricators for construction and fabrication services. The detailed design is scheduled to be completed by June 2015. The HAC Demonstrator is expected to be constructed, commissioned and fully operational by December 2015.

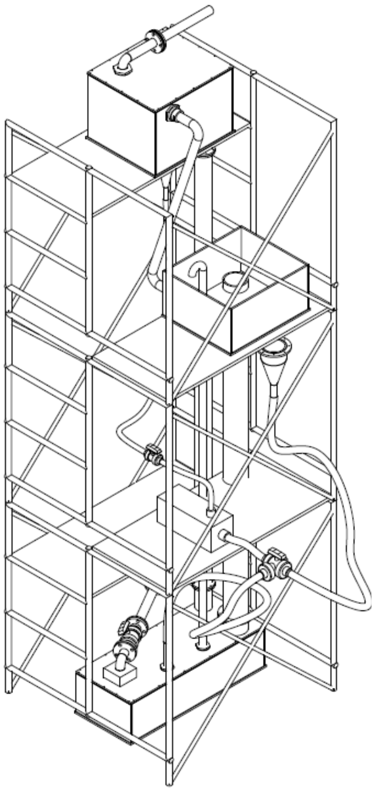

Fig. 7. 3D rendering of laboratory scale HAC test rig

Acknowledgements

The HAC Project Team gratefully acknowledges the Canadian Network Centres of Excellence, Ultra Deep Mining Network (UDMN) for project funding. Electrale Innovation Ltd., Cementation Canada Inc., the Centre for Excellence in Mining Innovation, Admira Distributed Hybrid Energy Systems Inc., Riventa Canada Inc. and Science North are also acknowledged for their contributions and support of the initiative.

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Appendix A

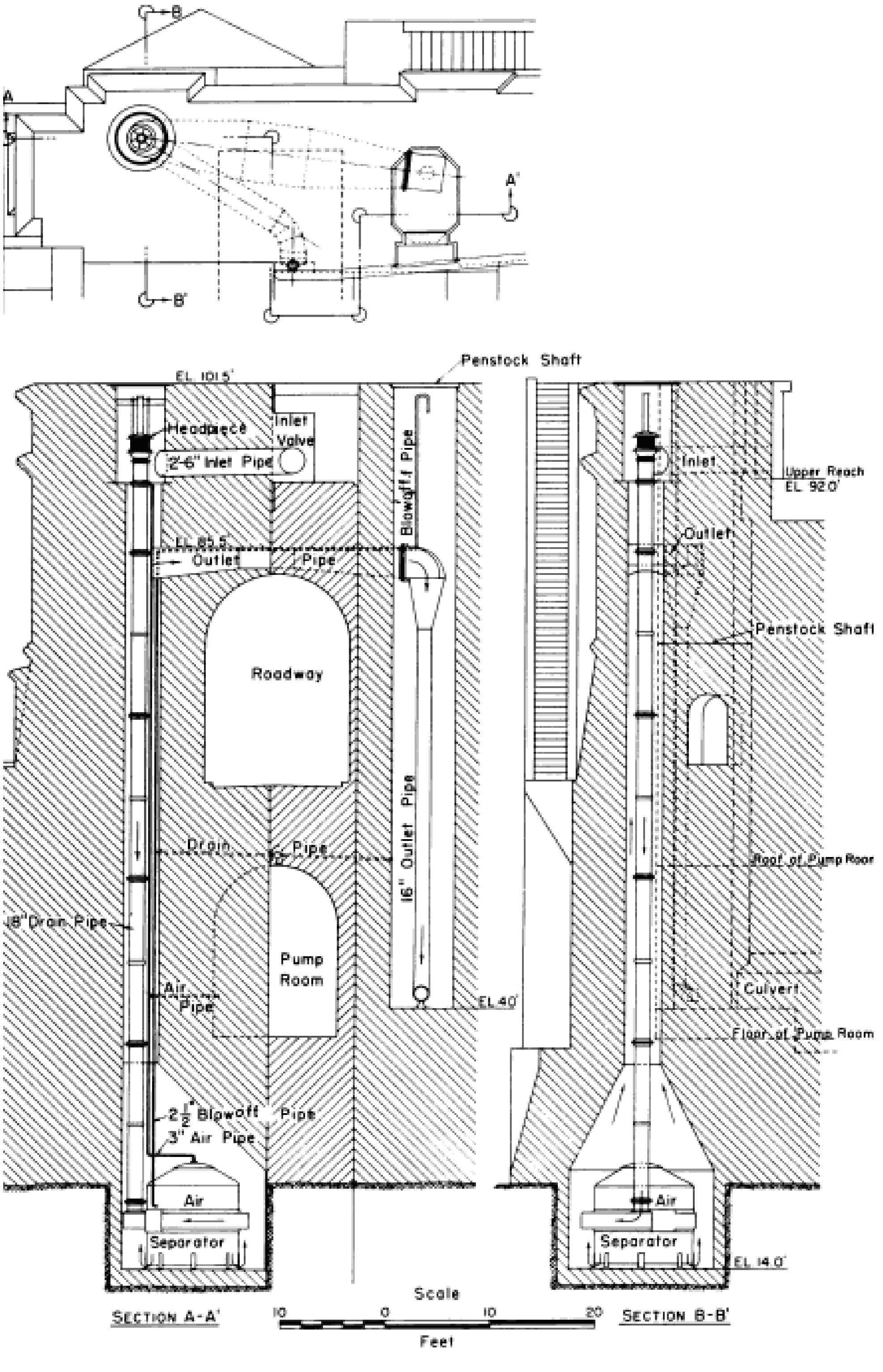

Fig. A.1. The Peterborough Lift Lock HAC installation showing the cyclonic air-water separator and coaxial downcomer and riser ducts. Source: Schulze [2].