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Multiobjective Optimization of Vortex Tubes Integrated in a Trigenerative Compressed Air Energy Storage System

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***Abstract*—A trigenerative compressed air energy storage system (CAES) integrating vortex tubes is investigated numerically. In this work, the system is sized according to the electrical power required for the community of Aupaluk in Nunavik (QC). The vortex tube parameters are optimized using a genetic algorithm to maximize the electrical efficiency of the system and the reduction in carbon dioxide emissions. The proposed system increases both the electrical efficiency and the reduction in carbon dioxide emissions when compared to the same system using a throttling valve in the discharging process. Details on the pressure and temperature levels at each step of the system are provided for the optimal solution. Finally, vortex tubes may generate liquid carbon dioxide from atmospheric air in CAES using high storage pressure. This new quadrigeneration CAES is one promising way to address the problem of climate change.**

***Index Terms*—Compressed-air energy storage system, Ranque-Hilsch vortex tube, thermodynamic model, multiobjective optimization.**

I. Introduction

Remote communities in Canada and abroad are dependent on diesel to generate electricity. Producing electricity in remote off-grid communities in Canada may cost as much as ten times the average electricity price [1] and generates huge amounts of greenhouse gas emissions.

Renewable energy could be used to generate electricity from locally available resources, but solar or wind energies are intermittent by nature. Energy storage systems are then deemed required to increase the penetrability of renewable energy sources in isolated communities [2]. Compressed air energy storage systems (CAES) are the second best storage option, just after the hydraulic pump [3].

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In a CAES, the electricity produced in excess is used to compress the ambient air. When the electrical demand is higher than the production of renewable energy, the compressed air expands in turbines to produce electricity. During this process, air needs to be cooled after the compression stage and needs to be heated before the turbines. In an adiabatic CAES, the heat produced during the compression stage is used to heat the air upstream of the turbines. A trigenerative CAES (T-CAES) stores both cooling and heating [4].

Another challenge with CAES system is the huge required storage volume. The two main industrial CAES currently under operation uses natural cavities as reservoirs [5]. When such cavities are not available, high pressure vessels are necessary to reduce the storage volume. Dib *et al.* [6] demonstrated that increasing the storage pressure from 40 to 200 bar greatly reduce the initial cost of the system. However, turbines cannot use air at a so high pressure. Throttling valves are then used to reduce the inlet turbine pressure, but generating at the same time large irreversible losses [7], [8]. Interested readers could find more information on the influence of the operating parameters on the CAES performance in [5], [9], [10].

Vortex tubes are an interesting alternative to the throttling valve. In its counterflow configuration (Fig. 1), a compressed gas is injected tangentially in the vortex tube. The tube includes two outlets : a cold one at the centre near the inlet and a hot one at the other end at the periphery. In a vortex tube, enthalpy is transferred from the cold stream to the hot stream. Consequently, the device may provide both useful heating and cooling at the same time. In comparison, the pressure is reduced in an isenthalpic process in a throttling valve.

Zhang and Guo [11] reviewed the many applications of vortex tubes. They also stated that actual applications of vortex tubes are limited because of their low thermal efficiency, the lack of quantitative design calculation tool and the lack of a

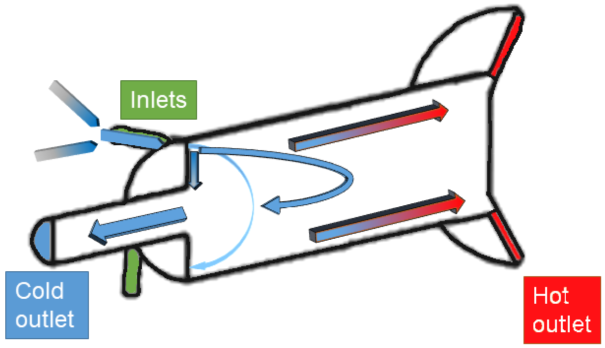

Fig. 1. Schematic view of a counterflow vortex tube.

validated working mechanism for the energy separation inside the tube. Optimization is then usually achieved using a trial and error approach in experiments.

Recently, a thermodynamic model achieved a good quantitive and qualitative prediction of the outlet temperature of vortex tubes working with air [12]. This model was used to optimize the exergetic efficiency of vortex tubes [13]. Among other conclusions, they found that the exergetic efficiency of vortex tubes increases when they are used at higher pressure. They proposed using vortex tubes to reduce throttling losses in a high-pressure system like CAES. However, as reviewed in [14], there is no experimental data available for vortex tubes working with high-pressure air.

In this paper, two vortex tubes in cascade replace the throttling valve in the T-CAES model of [8], [15] using a fixed storage pressure of 200 bar. The model of [12] is used for both vortex tubes. The T-CAES parameters are adjusted to fit the requirement of the remote community of Aupaluk in Nunavik (QC). Vortex tubes are configured using two multi-objective optimization methods to maximize their performance for this specific case.

II. Methodology

A. Thermodynamic modeling

Fig. 2 shows the proposed T-CAES configuration. When the renewable electricity production exceeds the demand, it is used to compressed air from the ambient (1) using three stages of compression. Compressed air is stored in an artificial reservoir. In addition, heat generated by compression is stored in a thermal energy storage system using water.

This system uses a reservoir pressure of 200 bar in an artificial tank, which is in the optimal storage pressure range identified by [16]. In addition, transporting equipment to remote northern locations is expensive, so a lower number of tanks is preferable even if it reduces the electrical efficiency of the system.

When the electric demand is higher than the production, the compressed air is used to generate electricity using one turbine and one air motor. However, the maximum inlet pressure for the turbine is 25 bar according to the actual commercial technologies. In the reference case, pressure is reduced from 200 to 25 bar by an isenthalpic process inside a throttling valve. The throttling valve links directly node 8 with node 14 in Fig. 2.

In the new proposed configuration, the throttling valve is replaced by two vortex tubes (VT) in cascade. Each VT produces heating and cooling from the excess pressure. After each VT, both flows go through heat exchangers that store the heating and cooling produced in the TES. Afterwards, both flows are mixed in the MC. Using a single vortex tube or mixing both flows in an ejector have also been investigated, both are not shown here for sake of brevity.

For the thermodynamic model, the experimentally validated T-CAES model presented in [15] is used. The current model uses the same values and assumptions than the original model, except for the capacity of the system that is scaled for the requirement of Aupaluk (see section II-C).

Vortex tubes are modeled using the model of [12]. It requires seven parameters to calculate the performance of a VT: the inlet Mach number (Ma_{in}), the axial Mach number in the cold outlet (Ma_z), the inlet mass flow rate ($\dot{m}_{in}$), the fraction of the mass going out through the cold outlet (μ_c) and the ratio of the cold outlet radius to the vortex tube radius (r_c/r_{vt}), the inlet total temperature (T_{0in}) and the inlet total pressure (P_{0in}). The model calculates the total temperature at the cold outlet (T_{0c}) and at the hot outlet (T_{0h}). It evaluates also the cold outlet pressure (P_c) and the vortex tube radius (r_{vt}).

The working fluid is dry air considered as a perfect gas with a fixed value for the specific heat at constant pressure (C_p). The perfect gas assumption does affect the magnitude of the temperature separation in vortex tubes. However, cooling in the throttling valve from the Joule-Thompson effect is small ($6°C$ when starting at $18°C$). Consequently, this assumption is adequate for this first analysis.

Finally, the pressure in the reservoir is considered as constant during the discharging process. In reality, as the pressure in the reservoir goes down, the heating and cooling produced by vortex tubes will be lower at the end of the discharge. Consequently, the benefit of vortex tubes will be higher than expected, but they will not reduce the performance of the system in any case.

B. Efficiency metrics

The main objective of the CAES is to store electricity by compressing a gas and recover this electricity later through expansion in a turbine. Consequently, the electrical efficiency (EE) is a crucial parameter, defined as:

$$\text{EE} = \frac{\dot{W}_{out} \cdot t_{dis}}{\dot{W}_{in} \cdot t_{ch}} = \frac{W_{out}}{W_{in}}, \tag{1}$$

with $\dot{W}_{in}$ the electrical power consumed during the charging process of duration t_{ch}, $\dot{W}_{out}$ the electrical power generated during the discharging process of duration t_{dis} and W the electrical energy consumed or produced during one cycle.

Even if the main objective is to produce electricity, the T-CAES allows production of useful heating and cooling at the

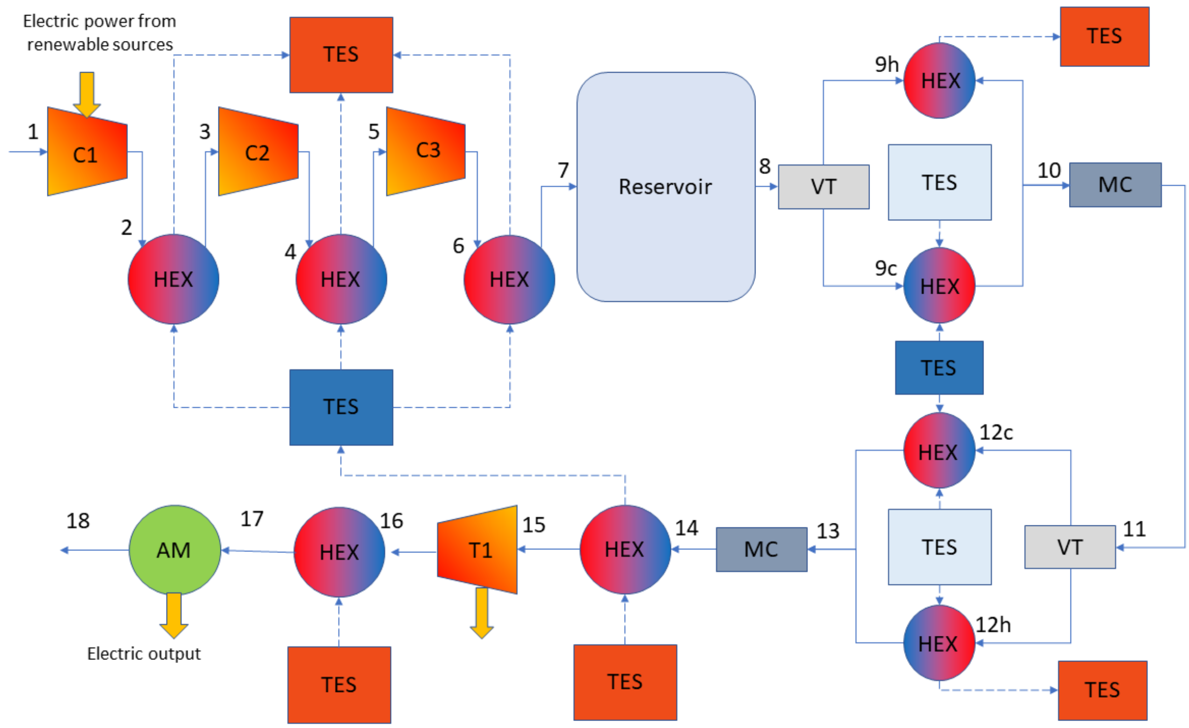

Fig. 2. Diagram of the proposed T-CAES system. C stands for compressors, TES for thermal energy storages, HEX for heat exchangers, VT for vortex tubes, MC for mixing chambers, T for the turbine and AM for the air motor.

same time. However, thermal and electrical energies are not equivalent. Different definitions exist to ponder these energetic outputs. In the COP, all types of energy have the same value. The comprehensive energy index of [4] ponders the heating and cooling by dividing the thermal energy by the average heat pump performance. Another possibility is to calculate the exergetic output of each heat flux [17], [18]. In this case, the heat output value depends on the temperature difference between the heat flux and the reference temperature.

In this paper, a new performance metric is proposed to better represent the particular context of northern remote communities where both electricity and heating are produced from diesel. Using the hypothesis that the electricity supplied to the T-CAES is produced using renewable, the reduction of carbon dioxide emissions (m_{CO2}) is calculated according to:

$$m_{CO2} = D\left(W_{out} \cdot \text{AFF} + \frac{Q_h}{\text{MHV} \cdot \text{AFUE}} + \frac{Q_c \cdot \text{AFF}}{\text{COP}_c}\right) \tag{2}$$

with m_{CO2} the mass of CO_2 (in kg) needed to generate the same amount of energy using diesel, $Q_{h,c}$ the heating or cooling energy generated during one cycle, D the typical emission rate of diesel fuel (2.66 $kg \cdot l^{-1}$) [19], AFF the average fuel efficiency of diesel generators in isolated communities in Canada (142 $l \cdot MWh^{-1}$) [20], MHV the mean heating value of diesel (38.4 $MJ \cdot l^{-1}$) [21] and AFUE is the annual fuel utilization efficiency of typical heating systems (80%).

C. *Sizing of the T-CAES for Aupaluk*

Aupaluk is a remote community with a population of 209 people located on the shore of the Ungava Bay in Nunavik. The total electrical generation capacity for this community is 780 kW [22]. To maximize the EE, the air is heated to the maximum possible temperature in this case ($117°C$) upstream of the turbine. From preliminary calculations, the EE is almost constant at 0.104 with or without vortex tubes for a fixed storage pressure of 200 bar. With this information, it is possible to size this system. To produce 712 kW, a mass flow rate of $9.56\ kg \cdot s^{-1}$ is necessary. To obtain a discharging time of 4 hours, the necessary storage volume is $720\ m^3$. Then, the input power is fixed to 5500 kW to get a charging time of 5 hours.

D. *Optimization algorithms*

A genetic multi-objective optimization algorithm is used to maximize the performance of vortex tubes in the T-CAES according the EE and m_{CO2} criteria. It is based on the function *gamultiobj* in Matlab. It is a controlled elitist genetic algorithm (GA) which is a variant of the non-dominated sorting genetic algorithm-II (NSGA-II) function described in [23].

Genetic algorithms have already been used to optimize an artificial neural network architecture, which predicts vortex tube performance [24]. For CAES, many authors used GA with success based on different performance criteria as displayed in Table I. It demonstrates that GAs are adequate for T-CAES optimization.

TABLE I
REFERENCE FOR MULTI-OBJECTIVE OPTIMIZATION OF T-CAES USING GENETIC ALGORITHM.

Reference	Objective
[25]	Exergy efficiency and total product unit cost
[26]	Exergy efficiency and exergy density
[27]	Total cost, offset of the CAES and energy saving ratio
[28]	Global exergetic efficiency
[29]	Round trip efficiency and annual cost saving

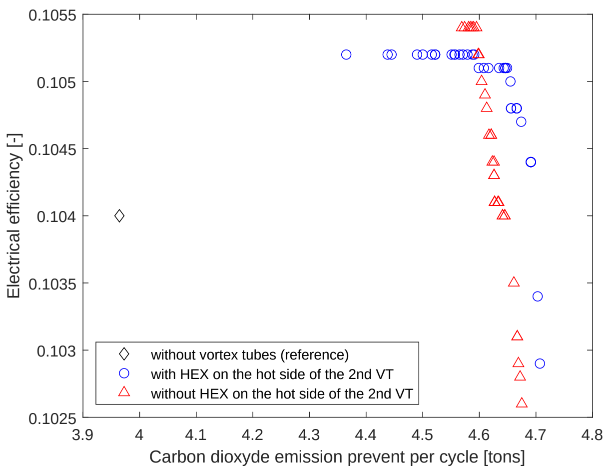

Fig. 3. Pareto front of the optimal solution obtained from the genetic algorithm.

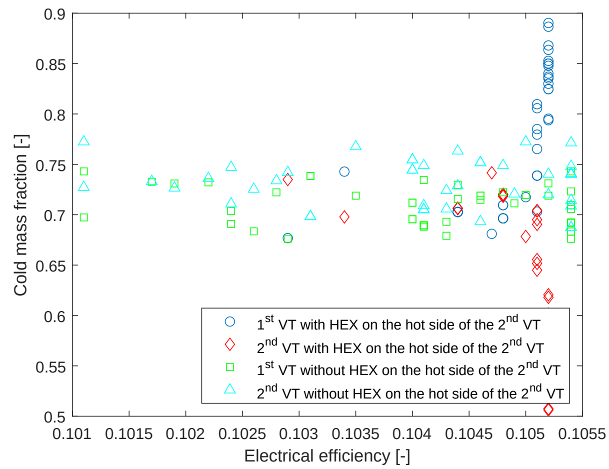

Fig. 4. Variations of the optimal cold mass fraction with the obtained electrical efficiency for the optimal population provided by the genetic algorithm.

For both vortex tubes, P_{0in}, T_{0in} and $\dot{m}_{in}$ are either fixed values of the problem or calculate from the previous vortex tube in the cascade. For both vortex tubes, the genetic algorithm identifies the optimum values of Ma_{in}, Ma_z, μ_c and r_c/r_{vt} as done by [13]. These parameters may vary in the ranges: $\text{Ma}_{in} = [0.7 - -0.95]$, $\text{Ma}_z = [0.1 - -0.5]$, $\mu_c = 0.5 - -0.9]$ and $r_c/r_{vt} = [0.3 - -0.6]$. Finally, the maximum number of generation is set to 6 in this case.

Note that another algorithm based on the minimization of the distance between the goal and the objective function was also tested, but the genetic algorithm performs better in the present case.

III. Results and Discussion

A. Vortex tube optimization

Fig. 3 displays the Pareto front obtained by the GA. Vortex tubes increase both EE and m_{CO2} when compared to the reference scenario using a throttling valve.

The electrical efficiency increases only slightly over 0.105 with the configuration presented in Fig. 2. As defined by Eq. (2), the electrical efficiency depends only on the electrical input and output. The input is a fixed value. The output depends only on the inlet temperature and pressure for the turbine and the air motor. Maximum input pressure at the turbine is limited to 25 bar. For the inlet temperature, it remains almost constant around $118°C$. This configuration generates approximately 11 MW of heat stored at $140°C$ and only 6.7 MW is used to heat air upstream of the turbine and the air motor. It is possible to increase the turbine inlet temperature above $118°C$ by increasing the size of the heat exchanger or its efficiency.

As for the m_{CO2} criterion, the curve shows a potential increase when the electrical efficiency goes down. In this configuration, Ma_{in} is maximized for both vortex tubes, but the pressure at the outlet of the second vortex tube is lower than 25 bar. This reduces the EE. However, the additional heating and cooling outputs produced by the vortex tubes have more impact on m_{CO2} than the reduction of the electrical production.

To select the vortex tubes, Fig. 4 presents the variations of the optimal μ_c found for both vortex tubes according to the resulting electrical efficiency. One can observe that, to maximize the electrical efficiency, one needs to maximize μ_c for the first tube and reduce it for the second one. In fact, this behaviour is related to the performance of the heat exchanger downstream of the vortex tubes. For the second vortex tube, reducing μ_c increases the mass flow rate through the hot outlet. This increase in the mass flow rate reduces the heat exchange on the hot side and increases it on the cold side. Consequently, the mixing temperature at node 14 in Fig. 2 is higher and it increases slightly the turbine inlet temperature.

To increase the turbine inlet temperature, the heat exchanger between node $12h$ and 13 in Fig. 2 is removed. The new Pareto front is shown in Fig. 3 and the variations of μ_c with the resulting EE are displayed in Fig. 4. This modification increases the maximum EE with a reduction of m_{CO2} caused by an increase od the heat consumption inside the process to preheat the air. The correlation between μ_c and the EE is then over. The remaining variations of μ_c in the population appear because the algorithm preserves a diversity in the population.

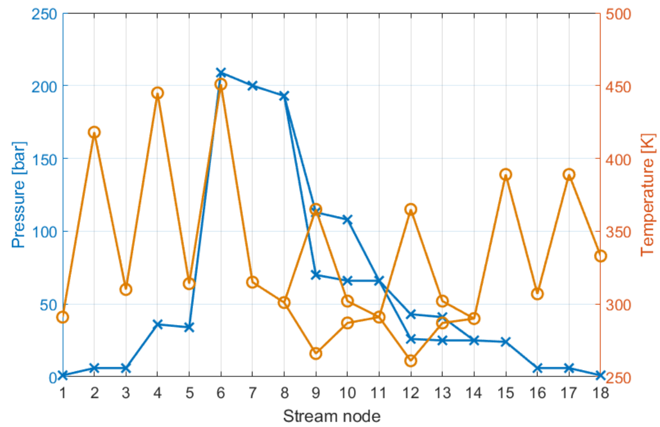

Fig. 5. Pressure [bar] and temperature [K] at each node of the system for a configuration corresponding to the inflexion point of Fig. 3 with the heat exchanger on the hot side of the second vortex tube.

Increasing the number of generations may progressively reduce this variability.

B. Description of the optimal solution

To maximize the utilization of heating and cooling, one needs to consider the temperature in addition to the amount of energy. Fig. 5 presents the temperature and the pressure of air at all nodes of the system presented in Fig. 2. The compressor produces heat at a higher temperature than the vortex tubes. This temperature is higher than the inlet temperature of the turbine and of the air motor. However, there is a time delay between heat production and consumption in that case.

As for the vortex tube, the heat produced at a temperature lower than the required inlet temperature for the turbine and for the TES. However, the heat is produced at the same time as its consumption upstream of the turbine. In this case, heat generated by the vortex tubes should be used to preheat the air before the turbine. Removing the heat exchanger between nodes $12h$ and $13h$ increases the temperature at node 14 from $17°C$ to $33°C$. Using the heat from the first vortex tube is more complex. One possibility could be to mix $9h$ directly with $12h$. Another possibility would be to use stream 14 to cool down stream $9h$.

Finally, CO_2 is in the liquid state at the cold outlet of vortex tubes (nodes 9c and 12 c in Fig. 5). Vortex tubes are good at separating liquid from a gas [11]. The proposed CAES using a storage pressure of 200 bar may capture atmospheric CO_2 at each cycle.

Considering a concentration of 400 ppm of CO_2 in the atmospheric air, the proposed CAES could generate approximately 5.6 tons of liquid CO_2 per cycle. The price of carbon in Canada was 30 \$/tons in 2020 and it is expected to rise up to 170 \$/tons in 2030 [30]. The value of the liquid CO_2 produced was approximately 170 \$/cycle in 2020 and it will rise up to 952 \$/cycle in 2030. Of course, liquid CO_2 is not an interesting byproduct for a remote location like Aupaluk. However, this system may be interesting in region with liquid CO_2 storage and transportation facilities as the Quest project and the Alberta Carbon Trunk Link [31]. In addition, it is simpler and cheaper than the combination of absorption units with CAES as proposed in [32] and [33].

However, the generation of liquid CO_2 was not expected at the beginning of this work. It did not appear in the configuration presented in Fig. 2. In addition, the effect of CO_2 separation on VTs, T1 and AM is not taken into account. For VT, the condensation process may reduce the temperature separation. Secondly, the reduced mass flow though T1 and AM will reduce the electrical output and the electrical efficiency. To analyze these effects, a model of vortex tubes considering a mixture of real gas and two-phase flow is deemed necessary, but experimental and numerical studies using high-pressure air or CO_2 in vortex tubes are required to develop this model.

IV. CONCLUSIONS

Even if electricity in Canada is produced in great part from renewable resources, remote communities are dependent on diesel for their electricity production. These locations could produce their energy from solar or wind energy, but due to their intermittent nature, an energy storage system is required to do so. Compressed air energy storage systems (CAES) is an interesting avenue to store electricity at a utility scale. However, when there is no suitable natural cavities to store air, high storage pressure vessels must be used to limit the storage volume. In that case, throttling losses during the discharging process become the major source of losses in the system.

To limit these losses, the use of two vortex tubes in cascade integrated in a trigenerative system is investigated numerically. To achieve this, the trigenerative CAES (T-CAES) model of [8] is combined with the vortex tube model of [12]. A genetic algorithm is used to identify the optimal working parameters of the vortex tubes on a T-CAES system sized for the remote community of Aupaluk in Nunavik (QC). The genetic algorithm draws the Pareto front of optimal solutions to maximize the electrical efficiency (EE) and the reduction in CO_2 emissions (m_{CO2}), a newly proposed criterion well adapted for remote northern communities.

Results demonstrated that maximizing the inlet Mach number for both vortex tubes maximizes m_{CO2}, but reduces the pressure available for the turbine. Consequently, it reduces the EE of the system. Surprisingly, the algorithm did find vortex tube combinations that increase slightly the EE. In this case, the cold mass fraction (μ_c) is higher for the first tube and lower for the second one. Different values of μ_c affect the performance of the heat exchangers located downstream and this combination increases the temperature at the turbine's inlet. To further increase this temperature, the heat exchanger after the second vortex tube may be removed. This change raises the EE of the system. In addition, optimal values for μ_c are now at a similar level for both vortex tubes.

Finally, details on the temperature and pressure levels at each node of the system were discussed. Heat provided by the compressor is high enough to further raise the turbine inlet temperature, but it has to be stored. Vortex tubes produce heat at a lower temperature, but it is available when the turbine needs it. Consequently, they can be used to preheat air without the need for storage. In addition, vortex tubes have the potential to be retrofitted on existing installations. In the Huntorf and the MacIntosh plants, air is throttling from $46-75$ bar to 42 bar [5]. This pressure difference is high enough to obtain an inlet Mach number of 0.5. This can be analyzed in a future work.

In addition, temperature and pressure levels indicated that atmospheric CO_2 may be liquefied within the vortex tubes in a CAES using high storage pressure. It could be an interesting by-product of the installation with carbon taxes expecting to rise quickly in the next 10 years in Canada.

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