Optimisation of vortex tubes and the potential for use in atmospheric separation

Gautam Agarwal, Zack P McConkey and Dr. John Hassard

Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom

E-mail: zackpmcconkey@protonmail.com

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Abstract
Climate change requires us to extract hundreds of gigatonnes of CO\textsubscript{2} from the atmosphere over the next few decades. This requires we develop and scale up viable technologies to sequester CO\textsubscript{2} from the highly dilute atmospheric concentrations. CO\textsubscript{2} gas freezes at $-78.5^\circ$C and thus, in principle, can be separated from air, the nitrogen in which begins to freeze at $-210^\circ$C. Vortex tubes were investigated as a potential method of carbon capture through a series of geometrical and procedural optimisations. Ambient air is compressed and then separated by temperature due to the action of the Vortex Tube. These optimisations determined an increase in system pressure and length at cold mass fraction of 40% led to increased cooling. The heat profile of pipes suggested radiative cooling as the vortex propagated. An optimised single tube reached a maximum cooling of $39.9\pm2^\circ$C. Vortex tubes thus present a method of separating and capturing components of the atmosphere. With further work, such as the successful combination of tubes in series, it is hoped that vortex tubes may prove to be a scalable solution capable of contributing to the reduction in atmospheric CO\textsubscript{2} using the solar cyclone tower to provide the energy and air flows required for this task.

Keywords: climate change mitigation, Ranque Hilsch, vortex tube, carbon capture, solar cyclone tower

(Some figures may appear in colour only in the online journal)

1. Introduction
Everyday lifestyles have become increasingly energy intensive. Since the industrial revolution, our dependence on fossil fuels has only increased. As a consequence, the carbon dioxide level in the atmosphere is the highest it has ever been in the last 3 million years and is climbing. In 2008, Hansen et al claimed that a limit of 350 ppm CO\textsubscript{2} in the atmosphere would maintain ice sheets and species, explaining the need to reduce the, then, value of 385 ppm so as to avoid doubling pre-industrial levels (280 ppm [1]) which is predicted to leave ‘a nearly ice-free planet’ [2]. Carbon dioxide concentration in the atmosphere exceeded 417 ppm in June 2020 [3]. With this concentration of greenhouse gases, temperature increase is inevitable. Scheffer et al suggest that a positive feedback loop can be seen between the warming of the planet and increase of greenhouse gases and it is suggested that this feedback will increase warming by 15%–78% [4]. This change would be catastrophic to ecosystems globally.

Since 1958, when Keeling started the first systematic study of atmospheric CO\textsubscript{2} [3] levels, humanity has deposited over 1100 gigatonnes (Gt) of CO\textsubscript{2} in to the atmosphere. Even assuming a 120 year mean atmospheric lifetime of that CO\textsubscript{2}, and an implausible immediate cessation of additional fossil fuel CO\textsubscript{2} reaching the atmosphere, over 1000 Gt must be
removed, preferably, within the next 30 years [5]. If we assume fossil fuel emissions do not immediately cease, we need to remove over 2000 Gt of CO₂ over that period, or an average of 60 Gt per year. This will require radical new approaches to carbon management.

Ranque-Hilsch vortex tubes have been investigated from as early as 1931 [6]. Over the subsequent 89 years, vortex tubes have increased in efficiency and applicability to industry; however, full understanding of the mechanisms involved has still eluded physicists. Despite this lack of comprehension, such tubes have proven useful: a refrigeration device with no moving parts and no need for a refrigerant or electricity has been found effective (for example) for spot cooling in machine shops. Using a jet of cold air, material chips can be removed while tools such as lathes or mills can be cooled. As well as this application, Vortex tubes have also been used in uranium enrichment plants and their implementation is being considered in natural gas facilities as a more effective method of separation than a Joule—Thompson valve [7].

The variables that control the temperature separation effect are investigated and optimised to obtain the coldest possible output. The feasibility of connecting multiple tubes to increase net cooling is also investigated.

Currently, vortex tubes are able to extract water from the atmosphere via the condensing and eventual freezing of humid air. It is hoped that this work can go even further to freeze other atmospheric gases.

If, in the future, vortex tubes are able to cool air down to the deposition point of CO₂, the technology could be a promising option for carbon capture when powered by renewable energy. The cheapest and most common method of carbon capture is afforestation: planting trees in disused agricultural land. Unfortunately for the full effect of this method to be realised, the trees must be fully grown which would take many years. Alternatively, direct air carbon capture can be used to start collecting immediately with the draw back that it is incredibly energy intensive [8]. While a possible solution based on Ranque-Hilsch vortex tubes has the merit of being highly scalable, relatively cheap, and with low intrinsic cost in carbon emissions, it inevitably will require significant energy. The energy expenditure is a topic to be addressed in future research. Fortunately, the Sun provides over 100000 TW across the entire globe, and just a small fraction of that could provide the necessary power. The solution we explore in this work involves the incorporation of the solar cyclone tower (SCT).

The SCT is an alternative source of energy design [9]. By creating a 1.2 km tall tower, of radius 200 m, on top of a greenhouse of radius 5 km, energy could be harvested from the large convection of air through this structure using a series of turbines. With an area of this scale, vast volumes of air would pass through the tower. Each tower is rated at 200 MW updraft electrical power (with an approximate 20% drop at night), going a long way to provide the necessary power.

2. Theory

A visualisation of the operation of a vortex tube is presented in figure 1. If a relative pressure difference exists between the input and two outputs of the tube, a chamber with static vanes causes the air to rotate as it enters the tube. As a parcel of air travels the length of the tube, warmer air concentrates at the periphery whereas colder air travels increasingly close to the axis of the tube. When these vortices meet the tapered stopper, seen in figure 2, the outer, hot, air is vented while the inner vortex is reflected back along the tube, exiting via the narrower output at the other end. This can be understood in general terms through Newtonian dynamics; however, some aspects have not been fully elucidated.

From the experimental discovery of the Ranque-Hilsch vortex tube, efforts have been made to optimise, explain, and commercialise the technology. One of the most promising existing applications is in the refinement of natural gas and oil. These working fluids are already under high pressure thus making them well suited to separation by vortex tubes. In this case, both phase and mass are used to purify the hydrocarbon components [7].

While advancements have been made in improving efficiency and vortex tubes have found a place in industry where conventional refrigeration is not feasible, consensus on the operating principle has not been reached. The most plausible option arises by considering the enthalpy H of the system. Air entering the tube is homogeneous in terms of temperature and pressure. When it is made to rotate by the vortex chamber, peripheral air has greater angular velocity than air near the

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**Figure 1.** Depicts the principle of the Vortex Tube. Air enters the vortex chamber causing the air to propagate in a vortex along the pipe. The vortex separates into an outer hot stream and an inner cold stream. As it reaches the end of the pipe, the inner cold stream is reflected by the tapered stopper, the hot stream exits the tube around the stopper while the reflected cold stream exits via the other end of the tube. Reproduced from [10]. CC BY 4.0.
Figure 2. The tapered stopper connected at the hot output of the vortex tube is used as a variable aperture to reflect the cooler central vortex. A rubber stopper is inserted into the pipe using a screw gauge to allow varying mass fractions of air to leave via the hot output. The housing connected this screw gauge system to the pipe.

axis. Enthalpy is related to internal energy $U$, pressure $P$ and volume $V$ by

$$H = U + PV.$$  \hspace{1cm} (1)

Enthalpy must be lower near the axis because the volume of a parcel of air must be smaller for a fixed radius as the parcel approaches the axis. Therefore, as the flow of air propagates down the length of the tube, parcels of air with higher internal energy due to thermal energy will transfer to the relevant distance from the axis to maintain this enthalpic gradient. Heat is exchanged between the forward travelling warm flow and the counter-propagating cold flow for the length of the tube [11]. The output of the system can be adequately described via energy conservation, using Euler’s Turbine formula,

$$T - \frac{\vec{v} \cdot \vec{\omega} \times \vec{r}}{C_p} = \text{constant},$$  \hspace{1cm} (2)

where $T$ is the stagnation temperature of the working fluid, defined as the temperature of a fluid at a point where all kinetic energy of the fluid has been converted to internal energy, $\vec{v}$ is the absolute velocity of the gas from the frame of reference, $\vec{\omega}$ is the gas angular velocity, $\vec{r}$ is the displacement from the axis, and $C_p$ is the specific heat capacity at constant pressure [12]. While (2) is consistent with the preceding explanation, it provides no physical insight as to the operating principle due to the fact that it is simply a mathematical description of the propagation. While the working principle is still subject to refinement, other useful empirical information and mathematical models have been obtained over time. It has been shown that the pressure difference required between the input and outputs can be relative, with vacuum pumps used to lower the output pressure below atmospheric pressure [13]. This is important as it increases the applicability of the technology.

Treating the vortex tube as a thermodynamic cycle mathematically shows the maximum coefficient of performance (COP) of cooling for vortex tubes is 2.5, whereas current refrigerants can achieve COPs of 15 [12]. Current refrigeration systems, however, are not optimised for the temperature range and drop required to capture CO$_2$, and with a larger drop, larger air compressors are required. Therefore, for this application, the difference in efficiency between Vortex Tubes and traditional refrigeration will have to be determined with experimental evidence.

Given the environmental importance of the intended carbon capture application, it is notable that vortex tubes require no environmentally detrimental working fluid, unlike current commercial refrigerants which are potent greenhouse gases and originally damaged the ozone layer.

The vortex is produced using a Wu nozzle seen in figure 3. The air enters the chamber and is introduced to the pipe through the angled slits. This nozzle has been found to produce between 2 and 5°C of further cooling than other models [14].

3. Method & results

An aluminium vortex tube of length 0.706±0.001 m was fabricated with a chamber design optimised by Wu et al., shown in figure 3. Aluminium was chosen due to the accessibility and rigidity of the material.

A compressed air cylinder was used to provide a pressure difference between the input and atmospheric pressure, set up as shown in figure 4(a). An air compressor is also suitable, but one with a suitably strong pressure output was unavailable to us. An RS AVM-09 anemometer was used to measure the wind flow rate at the cold aperture to calculate the proportion of air exiting the cold side of the tube, known as the cold mass.
Figure 4. The initial experimental setup with one vortex tube. Plot A shows a gas cylinder connected to the vortex chamber using an air line. Thermocouples at each output are used to measure temperature as well as an anemometer used to measure cold mass fraction. The vortex tube is held using clamps with two retort stands. Vortex tubes varied in length between 250 and 1000 mm. Plot B indicates a thermocouple placed at the cold output of the vortex tube.

Due to the requirement of a pressure differential for the operation of a vortex tube, this dependence was first investigated.

3.1. Pressure differential

Cold mass fraction and length of the tube were kept constant and cooling was investigated over a series of differing pressures. Pressures were altered using the canister valve while input and output temperatures were measured to determine cooling. Initially, readings were taken every 10 s over a 50 s period before later being taken every 10 s over a 180 s period.

The gas cylinder and safety apparatus used permitted a maximum input pressure of 7.5 bar. No effect was seen below 2.5 bar for the tube used. Between these pressures, temperature separation increased with increasing pressure, as seen in figure 5. With increasing pressure, associated cooling follows a negative inverse exponential, tending to a maximum. To determine the shape and parameters of this relationship, further data at higher pressures will be required.

As seen in figure 6, as pressure increases, an initial increase in cooling is seen before levelling off. This is attributed to the increased presence of cooling due to throttling at higher pressures. We see no steady state reached by the 4.5 bar measurements in this time period, however; at 7.5 bar we experience instability in the pressure at periods longer than 180 s and thus a consistent period was used for all measurements.

It is expected pressures less than 2.5 bar did not result in any cooling because a minimum initial wind velocity is required to maintain the cyclical flow of air through the length of tube and, for the length of tube used, this was only obtained for pressures of 2.5 bar and greater.

Figure 5. This demonstrates the effects of pressure on cooling over a short time period. These preliminary readings were taken to determine the most insightful pressure graduations to probe with longer readings, as our supply of compressed air was finite. It is seen that greater cooling is achieved at higher pressures. At low pressures we see limited throttling effects from the gas canister and so a slightly differing trend.

Figure 6. Shown is the cooling at differing pressures over a period of 180 s. Similarly to 5, we see greatest cooling at the greatest pressure. Higher pressures could not be investigated due to the constraints of the gas cylinders used. Similarly, for periods greater than 180 s pressure could not be sustained due to the emptying of the cylinder.
3.2. Cold mass fraction

Following varying input pressure, the variable aperture was adjusted to determine the relationship between cooling and the percentage of air directed towards the cold output (the cold mass fraction). By completely closing the variable aperture on the warm side, as seen in figure 2, the anemometer reading taken at the cold side is both the 100% cold mass fraction and maximum wind speed reading. The cold mass fraction is proportional to wind speed. Therefore, using the maximum wind speed as a reference, the cold mass fraction can be determined as a function of the position of the variable aperture.

The pressure at the input and the length of the tube were kept constant while the cold air mass fraction was altered. To achieve this effect, the tapered stopper was connected via a screw-gauge, as seen in figure 2. By measuring the wind speed when fully closed, the fraction of air escaping via the cold output could be estimated. The system was used over short periods of time so as to avoid extreme cooling of the compressed air canister used. This helped to maintain pressures over a series of cold mass fractions. During these short bursts, measurements of input and output temperatures were recorded to allow for the calculation of the optimum cold mass fraction for cooling.

As seen in figure 7, a maximum cooling effect is observed at approximately 40% cold mass fraction.

This empirically obtained relationship provides the optimal cold mass fraction required to create the desired temperature separation. It would be beneficial if cold mass fraction could be increased beyond 40%, as the mass of CO$_2$ that will deposit is proportional to this. This would be possible if other parameters can be sufficiently optimised to exceed the required cooling, such that the portion of cooling dependent on the cold mass fraction can be minimised.

3.3. Length to diameter ratio

The dimensions of the tube play a significant role in the performance achieved. The key parameter is the ratio between the length and diameter of the tube. This ratio determines the angular velocity of the flow and temperature separation as a function of length.

Aluminium tubes between 250 and 1000 mm were used, corresponding to ratios between 18.79 and 75.11. It was expected the performance would increase up to a length and then begin to decrease. This was assumed as over a certain length, pressure within the tube will decrease notably due to the larger working volume and when below a certain length we expect limitations in energy transfer between axial and peripheral flows due to insufficient thermal transfer in the available circulation time. Figure 8 presents the results obtained.

All lengths tested presented a decrease in cooling following a period of constant cooling. This arises because initially, all cooling is due to the effect of the vortex tube; however, as the experiment continued, the gas cylinder cooled when air was released as a gas into the tube. The lag between input temperature cooling and associated output air cooling due to circulation time inside the vortex tube resulted in the apparent decrease in net cooling. Therefore, it is expected using an air compressor instead of a cylinder of compressed air would avoid this downward trend.

The longest tube used, 1000 mm, had the largest associated cooling. Longer tubes will need to be fabricated to continue testing increasing length to diameter ratios to verify if a maximum is obtained.

The initial cooling observed increases as a function of length except for the shortest tube used (of length 250 mm). As seen in the temperature profile in figure 9, the behaviour of this tube deviates from all other lengths. It is suggestive of the existence of a critical length below which the vortex tube mechanism ceases to be observed. This is evidenced by...
3.4. Temperature profile

The effect of temperature separation as a function of length along the tube was of interest. To measure this, thermocouples were placed along tubes of various lengths at regular intervals, shown in figure 10. It must be noted the thermocouples measured the temperature of the tube and not the wind temperature at that location, though the two will equalise after a few minutes.

Figure 9 presents an analysis of temperature as a function of length along the tube and time of operation and is representative of the behaviour of most tubes tested. It is seen that closer to the input, a higher temperature is recorded. This suggests that heat is radiated from the uninsulated pipe. It also demonstrates the effect of the vortex tube in separating the air into peripheral hot and axial cold as we see a temperature greater than the input at all points along the pipe. The difference between the warmest point of the tube and the temperature at the warm aperture was 17.2±0.1 °C. This result is consistent with existing mathematical work by Fulton [15]. With the significantly higher temperatures at the surface of the tube, heat exchangers could be used to extract heat more efficiently than the outgoing air; however, this may disrupt the vortex mechanism due to enthalpy conservation. Further experimental work is required to determine the applicability of this method.

The results seen from the 250 mm tube differed to those seen for all longer tubes such that the increased wall temperature was not observed and with time, the entire length of the tube saw a reduction in temperature. This suggests different behaviour emerges below a critical length to diameter ratio of the tube. Joule–Thompson cooling may be the only effect that is seen in this case.

3.5. Single optimised tube

Using the data obtained from the previous experiments, a single tube was set up using the optimised parameters. This single tube achieved a cooling of 39.9±0.2 °C, shown in figure 11. The maximum was not maintained as the system reached the lowest temperature it could produce while the input continued to cool due to throttling. This results in a reduction in net cooling. The greatest cooling achieved during the experiments is still 48.5 °C away from the freezing point of CO₂ and so without significant improvements in efficiency, the system must be redesigned. We believe this redesign will involve the use of vortex tubes in series to allow for the progressive temperature drop necessary, as discussed in section 3.6.

The decrease in cooling may arise from a lower limit on the energy of the inner, cold, flow for the given parameters. This would suggest a lack of dependence on the input temperature with limiting factors being the input pressure and the length of the tube as these are the most likely to aid with energy transfer between the streams.

3.6. Linking tubes

Following experimentally optimising single tubes, the feasibility of cascading tubes was investigated. Two vortex tubes were set up such that the cold output of one was connected to the input of the second tube, as shown in figure 12.
Figure 10. This photograph depicts the placement of sensors along the 250 mm pipe to determine the heat profile of the Vortex Tube.

Figure 11. Depicted is the cooling achieved by a single optimised tube of length 1000 mm, cold mass fraction 40%, and at pressure 7.5 bar. A maximum cooling of $39.9 \pm 0.2$ °C was achieved over the 180 s period. This drops over time as the system cannot produce a lower temperature, however the input continues to cool due to throttling.

Figure 12. Experimental setup for testing cascaded vortex tubes. By directing the cold output of one tube into the input of the second, it was hoped a lower overall temperature would be obtained. Reproduced from [10], CC BY 4.0.

The experiment was conducted at 4.5 bar, with a single tube tested first and then the combined performance measured.

Figure 13. The performance of a single vortex tube, shown in subplot (a), is compared to the results from two cascaded Vortex Tubes, seen in (b). Two tubes were altogether less efficient than a single tube with the current experimental setup.

As seen in figure 13, the total cooling obtained by cascading two tubes together was less than what was achieved with a similarly set up single tube. This may be because of the difference in pressures between the outputs of the first tube. The warm output is unchanged and remains at atmospheric pressure. The cold output, however, leads to the second vortex Tube and, therefore, air experiences greater resistance exiting the cold aperture. Thus, the performance of each tube is diminished compared to when operated individually. This is in agreement with the data presented in figure 13 where the cooling achieved by the second tube, with both outlets open to the atmosphere, was greater than that of the first tube.

The change of medium, into the reinforced tubing used to link, may also limit performance. This could be minimised by...
shortening the linking tubing. As seen in figure 13, the total cooling is less than the sum of the cooling of both tubes. This arises from the warming of air between the output of the first tube and input of the second tube. Reducing the path this air travels and improving insulation at this step will reduce this source of energy loss.

Reconfiguring the setup with a vacuum pump may allow a successful cascade of vortex tubes. If it is placed between the cold output of the first tube and the input of the second tube, the aforementioned problem of increased cold output resistance in the first tube will be resolved, leading to a larger net cooling. The energy cost and resulting efficiency will have to be determined experimentally. In addition, if the vacuum pump solution is successful, the ideal number of linked tubes will be an additional parameter to experimentally optimise.

3.7 Errors

3.7.1 Pressures. Pressure was measured using a pressure gauge attached to the gas canister, giving an error of ±0.5 bar. As the canister emptied, the pressure had to be adjusted via a valve to maintain the chosen pressures. This adjustment was made again using the pressure gauge as a guide.

3.7.2 Windspeed. An anemometer was placed at a distance of 4 cm from the cold output to measure windspeed as an analogue for cold mass fraction. The error given by this device was ±0.01 ms⁻¹, however; these measurements were recorded with an error of ±0.1 ms⁻¹ as inconsistency in flow due to the nature of venting the air to atmosphere made recording to a higher degree of accuracy impractical. The change in windspeed in the 4 cm gap can be negated as the cold mass fraction is determined using a ratio of total measured windspeed to the measured windspeed at specific stopper depths, therefore the consistent 4 cm gap is inconsequential.

3.7.3 Temperature. Thermocouples were attached at either end of the vortex tubes measuring the temperature of the air. These gave error values of ±0.1 °C. As well as measuring outputs, measurements were made along the length of the pipe. These measurements were of the change in temperature of the aluminium pipe and so the change in medium causes inconsistency across measurements. In the case of heat profiles, this was inconsequential as all temperature measurements were made on the metal pipe; however, for all measurements, input temperatures were measured by measuring the temperature of the aluminium endpiece of the airline. This could affect all measurements except the heat profile of the pipe. Due to the 10% difference in the specific heat capacities of air [16] and aluminium [17], it is estimated an error of this order could come into effect.

Errors in measurement arise from the accuracy of the thermocouples, pressure gauges, anemometers, metre rules, and Vernier callipers used. As well as the obvious errors from these measurements, there is also error associated with the cooling of the gas as it is expelled from the gas canister. This depressurisation causes a throttling effect through the air line as well as causing the canister itself to cool. If this cooling from depressurisation is at a rate greater than that caused by the vortex effect, the cooling achieved may be offset by this initial cooling.

4. Discussion

Compared to traditional refrigeration cycles, vortex tubes have an advantage when dealing with large volumes of moving air. Refrigeration cycles are limited by the rate at which energy is transferred between the refrigerant and the target object. As a result, the traditional method is efficient for slowly moving gas (at a few meters per second), like in air conditioners, or fixed volumes like in residential refrigerators.

In vortex tubes, the velocity of the working fluid depends on the pressure difference between the input and outputs. Therefore, the efficiency of vortex tubes is not limited by the speed of pumping of a secondary media.

The maximal peak cooling achieved following all optimisations tested was 39.9±0.2 °C. Additional optimisation must be considered for vortex tubes to become a viable solution. Limitations of the experiments carried out included an inability to test longer lengths of pipes than 1000 mm and so a maximum length for increasing the cooling was not observed. Similarly, no further pressures could be tested due to canister limitations and as such, no upper limit to effective pressure was found. The most significant avenue for improvement remains the successful cascading of vortex tubes to add together the cooling effect.

Another promising design optimisation to be investigated is the diverging vortex tube, as seen in figure 14. Experimental work by Chang et al., shows that this design is more efficient for temperature separation than the straight vortex tube design tested [18]. There is no consensus on the optimal angle of divergence, with angles tested ranging from 2 to 8 degrees. Manufacturing such tubes is more involved, thus presenting a barrier to experimenting, but with temperature separation of 44.8 °C achieved at 4 bar with a 4 degree angle of divergence, the potential for improvement is significant [18].
It is envisioned the tubes can be deployed on a large scale in conjunction with the SCT. Like with natural gas applications, the SCT creates a natural pressure gradient due to the height of the tower [9]. This can supplement the gradient created by air compressors and vacuum pumps, powered by energy from the SCT to accelerate ambient air above 20 m s$^{-1}$. Exhaust warm air can continue up the SCT, supplementing its operation, and energy can be recovered from cold air as it mixes with ambient air to reduce energy expenditure.

5. Conclusion

So far, carbon capture by deposition has not been commonly applied due to the difficulty of attaining the cold temperatures required significantly below room temperature for a large, moving volume. Vortex tubes are an alternative method of temperature separation to traditional refrigeration that is better suited to the application. Experimental data shows cooling is optimised for a cold mass fraction of 40%, and that cooling increased with a relative pressure increase and an increasing length to diameter ratio of the pipe. Once optimised, the peak total cooling for a single tube was 39.9±0.2°C.

While this alone is not sufficient in most cases to cool air to the required ~78.5°C for carbon capture, it sets the optimisation process on the right track. Lab constraints meant pressure differences larger than 7.5 bar could not safely be tested. To achieve the cooling required to remove CO$_2$, further work in optimisation, such as finding the pressure and length limits, must be carried out.

A significant avenue for improving performance lies in successfully cascading vortex tubes. Through experimental data, it was identified reducing the effective pressure at the cold outlet of the first tube may allow a successful array of tubes.

Experimental observations about the temperature profile of the tube are of interest as this can allow for more efficient heat extraction from the system from the surface of the tube, which increases the prospects of implementing vortex tubes in industry.

With further work, it is hoped vortex tubes will become a viable solution to carbon capture. Nonetheless, this work indicates the capabilities of vortex tubes and we expect other suitable applications of separation and cooling will arise.

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ORCID IDs

Gautam Agarwal  https://orcid.org/0000-0002-3533-089X
Zack P McConkey  https://orcid.org/0000-0002-9623-3022
Dr. John Hassard  https://orcid.org/0000-0003-4681-001X

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