Experimental Demonstration of Vortis's Spinning Disc Separator for CO_2 Capture

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Executive Summary

Vortis Carbon Corp ("Vortis") is a carbon management company based in Calgary, AB, focused on developing simple and affordable ways to capture, convert, and market carbon emissions. Over the past seven years in partnership with the Alberta Innovates, University of British Columbia's Clean Energy Research Centre (CERC), Natural Gas Innovation Fund (NGIF), NanosTech, and University of Calgary we have developed a novel approach to carbon capture that uses motion and vortices to separate CO_2 based on its molecular weight.

While molecular separation has been proven commercially in applications such as uranium enrichment, it has been overlooked for gas separation and carbon capture due to the need for high rotational speeds, energy, and costs required to create the high G-forces necessary for separation. Vortis has developed a novel way to overcome these hurdles by creating high G-forces at extremely low RPMs and energy. This approach is a new technology pathway for carbon capture.

The current landscape for carbon capture focuses mainly on chemical, sorbent, or membrane technology. These pathways rely on expensive materials, are complex, and have high energy use. The challenges are further exacerbated by differing purity levels of CO_2 based on specific capture applications, which creates high installed capital and operating costs for the technology and ultimately creates high capture costs and low capture efficiency for operators. Vortis's Spinning Disc Sperator (SDS) technology promises to significantly lower the complexity and energy requirements for carbon capture, especially in low-purity CO_2 applications. Based on preliminary modelling at the University of British Columbia's CERC, Vortis' SDS could offer an order of magnitude reduction in input energy requirements while reducing the capture costs by 70% and doubling the capture efficiency when compared to amines.

Since 2023, Vortis has been engaged in the experimental design and optimization of its Spinning Disc Separator (SDS) to reduce carbon abatement costs for emitters. This project involved bench-scale prototyping of the SDS technology, complemented by computational fluid dynamics (CFD) modeling to design, test, and refine the separation process.

Initial SDS designs provided valuable insights into how vortex structures generate forces sufficient for molecular separation. However, early prototypes faced challenges in maintaining the necessary residence time for effective CO_2 separation. In response, Vortis developed a simplified design that produced a vortex separator design, which produced a simplified, sustained vortex system, significantly improving system stability.

Subsequent testing demonstrated successful CO_2 separation from mixed gas streams. However, while the revised design proved the technology's ability to separate CO_2 mechanically, the initial separation capacity of 45% remained below commercial viability thresholds. To enhance performance, Vortis integrated the vortex separator with a downstream absorbent system. This hybrid approach leveraged the cooled, concentrated CO_2 stream generated by the vortex separator, resulting in improved separation efficiency and bringing the system closer to commercial viability.

Vortis conducted process modelling using ASPEN Plus® and ASPEN Adsorption® to evaluate the economic feasibility and life cycle emissions of its optimized carbon capture process for a 1,000,000-tonne-per-year commercial-scale facility. In the optimistic scenario, economic modelling demonstrated a 60% reduction in energy consumption compared to amine-based systems, achieving an energy requirement of 0.8 GJ per tonne of CO_2 captured. Additionally, capture costs were estimated at $45.70 per tonne of CO_2, highlighting the potential for significant cost savings and improved efficiency.

Introduction

Sector Information

Carbon capture is a crucial tool in the transition to cleaner energy, helping to decarbonize industries that heavily rely on fossil fuels. However, the high cost of carbon capture remains a major challenge due to factors such as CO_2 concentration, contamination, emission flow rates, and the dispersion of sources. These challenges make it difficult for organizations to reduce their emissions while managing the rising costs and liabilities associated with emerging carbon regulations.

In Canada, approximately 30% of total greenhouse gas (GHG) emissions come from small or dispersed sources (<100 ktCO_2eq/year), for which existing carbon capture technologies are neither economically viable nor technically suitable. These emissions primarily come from key industries such as natural gas, petrochemicals, mining, steel manufacturing, and cement production. While these sectors are critical to decarbonization, they lack scalable solutions for remote areas, small-capacity operations, and distributed carbon collection and transportation. Current commercial technologies, such as amine-based capture systems, are optimized for large-scale facilities but are difficult to scale down to small and scattered emission points.

The Case for Natural Gas

In Canada's natural gas sector, 500 out of 800 processing facilities are distributed across Alberta. These facilities, including processing and distribution operations, contribute about 3% of total industrial emissions in Canada. Provincial emissions from the sector are distributed as follows:

- Alberta: 6.7 MtCO_2e/year
- British Columbia: 0.49 MtCO_2e/year
- Ontario: 0.935 MtCO_2e/year
- Saskatchewan: 0.454 MtCO_2e/year

Introducing adaptable and cost-effective carbon capture technologies for the natural gas industry could reduce GHG emissions by approximately 8 MtCO_2e/year nationwide. This reduction represents 1.2% of Canada's total GHG emissions and 2.35% of Alberta's emissions. Lowering the GHG intensity of Alberta's natural gas sector would not only cut production costs and emissions penalties but also enhance access to global export markets. By supplying affordable, lower-emission energy carriers, the industry can play a significant role in the global energy transition.

Technology Gap

Carbon capture can play an essential role in the energy transition by decarbonizing many industries that rely heavily on fossil fuel energy. Today the cost to capture carbon is prohibitively high due to factors such as concentration of CO_2, contamination, flow rates, and dispersion of the emission sources. These factors create significant challenges for organizations to reduce their emissions while mitigating potential emission abatement costs, and liabilities, as policies focused on regulating carbon emissions, come into force.

The current rate of innovation in Carbon capture technologies is slow. There are no transformative capture technologies offering step-change reductions in energy and costs, especially for low CO_2 concentration applications. We have observed only an incremental decrease in energy and costs of current incumbent separation technologies.

Vortis's SDS takes a novel approach to carbon capture, which promises to deliver a transformational reduction in costs for carbon removal in low CO_2 concentration applications, far superior to current technology pathways. The SDS doesn't rely on traditional methods such as amines, sorbents, or membrane for capture. Vortis's SDS uses mechanical separation, "separation by motion," which exploits the differences in molecular weights of CO_2 and other gases. This provides a sustained competitive advantage because performance is not tied to the concentration of CO_2 but differences in the molecular weight of the gas, making the system's performance significantly more uniform across a greater spectrum of CO_2 concentrations.

Compared to incumbent separation technologies, the SDS main competitive advantage is that it could significantly reduce the energy required to capture carbon in many low CO_2 concentration applications by order of magnitudes. This translates into significant cost savings and significant improvements in the capture efficiency of the process. For example, when comparing the SDS to traditional Amines capture, the energy required to capture a tonne of CO_2 is over 85% lower, translating into a 80% cost reduction in capture costs. More importantly, because Amines use natural gas and heat for regeneration, there is a hefty carbon penalty for the system making the system only 50% efficient in removing carbon. The SDS is purely electric and is upwards of 90% efficient, and in some scenarios where renewable energy is available, 99% efficient. Moreover, the SDS also provides a simpler module design that intensifies the process, lowering capital requirements relative to other competing processes.

Project Description

Technology Description

Vortis is developing a novel approach for capturing CO_2 from point source emissions. Our system uses rotational motion and vortices in gaseous flows to separate CO_2 based on molecular weight.

Vortis's vortex separator uses rotating vortices to separate mixed gases based on their molecular weight . In concept, flue gas is introduced in a vortex-generating space. As the system of vortices rotates, they generate localized high centrifugal forces. As a result, the heavy gas species (e.g., CO_2) move towards one side of the unit while the lighter fractions (N_2, O_2) move to other areas. Collection nozzles extract the gases at a higher purity than initially fed. Trace contaminants present in the flue gas accompanying the main products can be further removed by commercially available technology standards in flue gas cleanup.

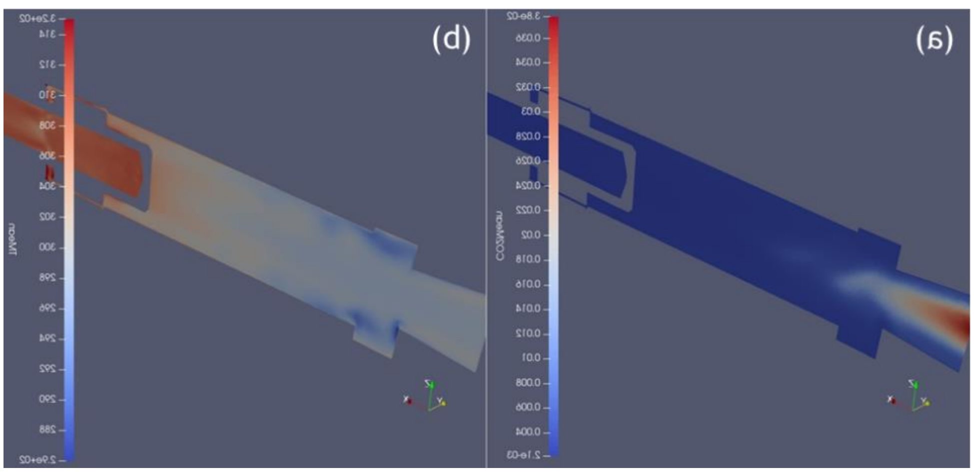


Figure 1- Vortis vortex separator (a) CO_2 concentration profile and (b) temperature profile using a 21 %vol.CO_2/N2 mix in the feed via Computational Fluid Dynamics (CFD) simulation.

As a first prototype, the Vortis team assembled a vortex separator device (Figure 1 and 2). Using this device, we could create strong and sustained vortices to test the concept of vortex separation aligned with results obtained via CFD . In the vortex generator, the compressed gas is ejected through a chamber, forming a spinning movement, known as primary vortex, toward the control valve. Some gas is released in the control valve at a higher temperature than the inlet. The rest of the gas bounces back, spinning through the center of the tube, making a secondary vortex. To maintain a momentum balance, the central vortex gives away kinetic energy in the form of heat and exits the tube on the opposite end as a cold stream.

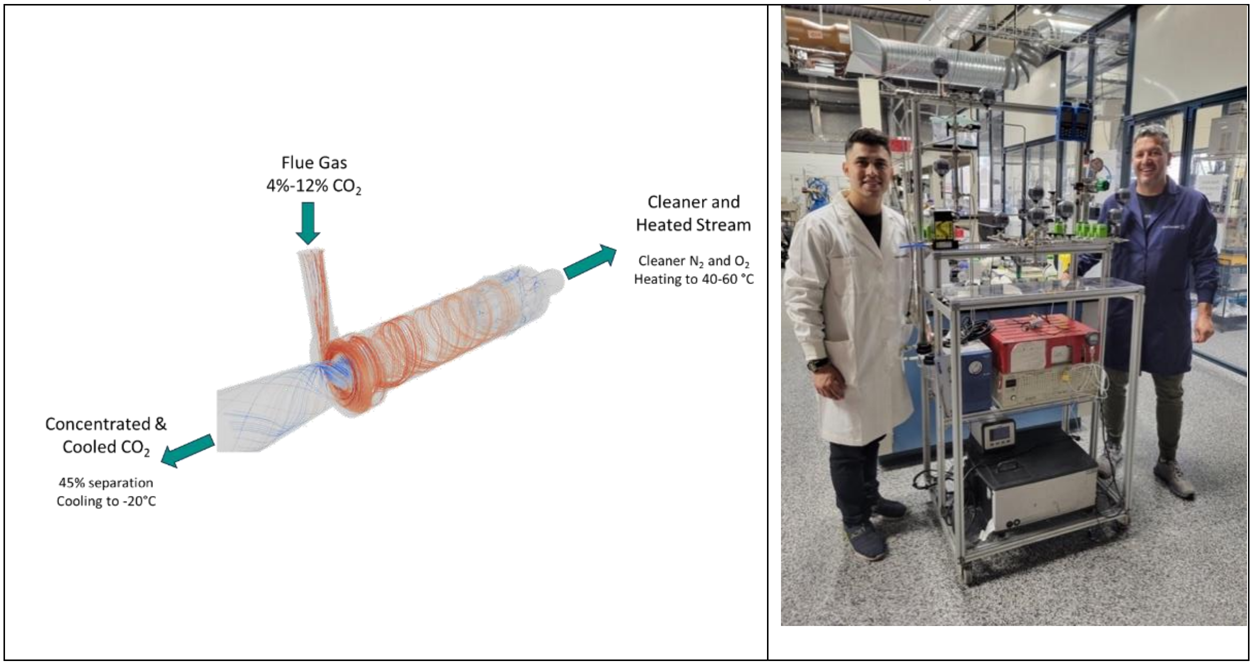


Figure 2- Schematic of the primary vortex separator from CFD modelling. The red and blue spirals on the right and left, respectively, show the vortex flow (streamlines) on the hot and cold sides.

Project Objectives & Metrics

Table 1- Clean Resources Metrics

Metric	Project Target	Commercialization / Mobilization Target
Investment in 4 Core Strategic Technology Areas	Develop one (1) Clean Technology for Carbon Capture	Develop a modular, electric, high-efficiency carbon capture technology for gas compression stations. Engage with industrial user for development partnerships
TRL advancement	Progress from TRL 3 to TRL5	Initiate laboratory testing and integrate partner for pilot development
Future Capital Investment	If successful the next step of the development may bring to Alberta over $7 million in capital investment.	Work with user partnership and VCs to obtaine the necessary capital
Field pilots/demonstrations	Develop design for one (1) pilot unit design	Work with engineering partner in the design development based on the project's results
Collaborators	Continue collaboration with three (3) partners including UBC, Nanostech, and engineering company for the design and manufacturing of prototype and pilot units	Maintain and manage collaborations via regular meetings and results sharing

Publications	Publish one (1) article on a peer-reviewed journal	Article already on the go, journal identified, waiting from laboratory results to finalize the submissions
Knowledge Mobilization	Attendance to two (2) conferences and trade shows to showcase the project achievements	Select proper venues to present project results and prepare material for presentation
Students Trained (M.Sc., Ph.D., Postdoc)	Train two (2) student during the execution of the project	Work with UBC in applying for NSERC grant to hire students before the project starts
Sector HQP Trained	Train two (2) new HQP on new technologies for Carbon Capture	Look to hire staff as needed to achieve the project's goals
Existing Sector HQP Jobs Retained	Retain three (3) HQP on new technologies for Carbon Capture	Provide our staff the proper conditions for effective work and connect the work with a longer term vision associated with decarbonizing our economy
Jobs: Actual new jobs created from project	Create over 30 full-time high skilled jobs in Alberta for the commercial scale-up of the SDS including the design, build, and operation of future laboratory pilots, and commercial demonstrations.	Establish a scale-up strategy to define best pathway to market access and talent acquisition
GHG emissions: Projected reductions from future deployment (to 2030)	Reduce Alberta's emissions by 8 $MtCO_2eq$/year through commercial deployment by 2030	Engage with users during the project to look for development and implementation agreements with industrial partners

Table 2 - Program Specific Metrics

GHG emissions: Actual reductions from project	Project Target	Commercialization / Mobilization Target
# of alternative energy technologies deployed	Develop one (1) Clean Technology for Carbon Capture	Develop a modular, electric, high-efficiency carbon capture technology for gas compression stations. Engage with industrial user for development partnerships
$ intensity cost reduction on production of CO_2	Reduce cost of CO_2 capture by 50%	Monitor technology for energy and cost reduction with respect to incumbent CO_2 capture technologies

Table 3 - Project Success Metrics

Metric	Project Target	Commercialization / Mobilization Target
Capture efficiency	Beta prototype is achieving 76% or more of capture efficiency for flue gas feed	Measure capture efficiency, identify ways of improving performance if needed
CO_2 purity	The CO_2 purity in the product stream is above 96 vol%	Measure CO_2 purity, identify ways to improve performance if needed

Energy use	The energy use per tonne of CO_2 capture is in the range of 20-40 kWh/tonneCO_2	Monitor energy consumption and extrapolate to industrial capacity based on prototype performance. Identify ways to improve performance if needed
CFD model uncertainty	CFD model projections below a 5% deviation from the experimental data	Validate model results with experimental data. Optimize model parameters to achieve a good fit to experimental data

Methodology

Facilities

A bench-scale prototype was developed and tested at the Vortis research facility in Calgary, Alberta. The vortex separator, sourced from a third-party supplier, was integrated into a custom-built bench-scale testing apparatus designed to capture 2 kg of CO_2 per day from a mixed gas stream (CO_2, N_2/O_2). To ensure accurate control and measurement of gas compositions at both outlets, the system incorporated mass flow controllers, gas analyzers, and temperature sensors. Additionally, gas chromatography (GC) analysis was performed to further characterize the gas streams.

During the optimization phase, an absorption step was introduced downstream of the vortex separator to assess the combined carbon capture efficiency of the system. Several modifications were implemented throughout the testing process to enhance separation capacity and improve overall system performance.

Methodology

Vortis followed a structured, three-phase process to develop and scale its mechanical CO_2 capture technology:

1. **Initial Experimental Validation –** Using computational fluid dynamics (CFD) data from the University of British Columbia, Vortis designed, built, and tested an Alpha prototype to evaluate feasibility.

2. **Optimization –** Insights from experimental testing guided the implementation of an optimization plan to enhance the prototype's capture efficiency and rate. A refined design was then developed and tested.

3. **CFD Modeling for Pilot Design –** Experimental data was used to build advanced CFD models, providing critical insights for scaling up the technology and designing a pilot system.

Beyond experimental and analytical testing, process simulations were conducted using ASPEN Plus. These simulations generated key scale-up data, supporting techno-economic analysis and life cycle assessment, which provided valuable insights into the technology's commercial viability.

Project Results

Milestone #1 – Test Bench Scale Prototype with Flue Gas Mix

Task Description	Deliverable
1.1. Run the available alpha prototype with flue gas mix	
1.2. Identify performance limitations compared to runs done with the ideal gas mix done previously.	
1.3. Identify potential design improvements for flue gas and evaluate potential impacts via CFD.	Testing report, data analysis, and proposed design modifications

Experimental Testing

Experiments were conducted to assess the performance of a vortex separator for CO_2 capture using an ideal gas mix (CO_2/N_2) and simulated flue gas (CO_2/Air). The tests were performed at ~4.5% CO_2 concentration, mimicking emissions from a natural gas power plant. The vortex separator was evaluated at inlet pressures of 2, 3, and 4 bar at room temperature (23-24°C).

The separation capacity was measured as the difference in CO_2 concentration between the cold and hot flows. The highest separation efficiency observed was 45% at yc=0.3 and 4 bar, while the lowest was ~1% at yc=0.5 and 2 bar. The separation was enhanced at yc values of 0.3 and 0.8, while minimal at yc=0.5. The results indicate that the system is highly sensitive to pressure fluctuations, a behavior requiring further investigation.

Increasing pressure improved separation capacity, aligning with existing literature. However, economic trade-offs exist due to energy penalties associated with higher pressures. The presence of O_2 in the air had varying effects: reducing separation efficiency by ~2% at yc<0.5 but enhancing it by 3-8% at yc>0.5, suggesting different separation mechanisms at play.

(a) CO_2/N_2 (b) CO_2/Air

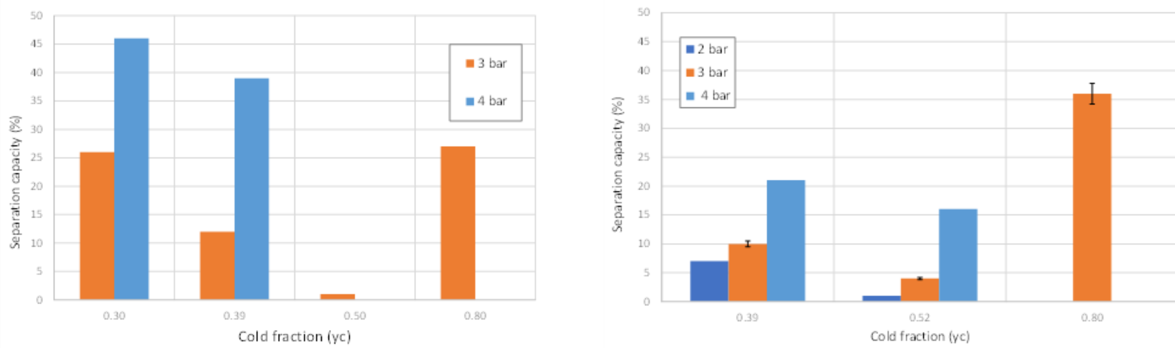


Figure 3- CO_2 separation capacity for 4.5 %volCO_2 in the feed for (a) CO_2/N2 and (b) CO_2/Air mixtures at 2,3, and 4 bar of inlet pressure and various cold fractions.

Temperature Effects

The vortex separator also exhibited significant temperature changes. Cooling was more pronounced at lower yc values, while heating increased at higher yc. The highest cooling capacity (-40°C) was observed at yc=0.3 and 4 bar, while heating capacity peaked at 35°C at yc=0.8 and 4 bar. No significant temperature differences were observed between CO_2/N_2 and CO_2/Air mixtures.

While the vortex generator's separation efficiency (~50%) is lower than conventional amine-based systems (~95%), its strong cooling effect may enhance the performance of downstream CO_2 capture units.

(a) CO_2/N_2 (b) CO_2/Air

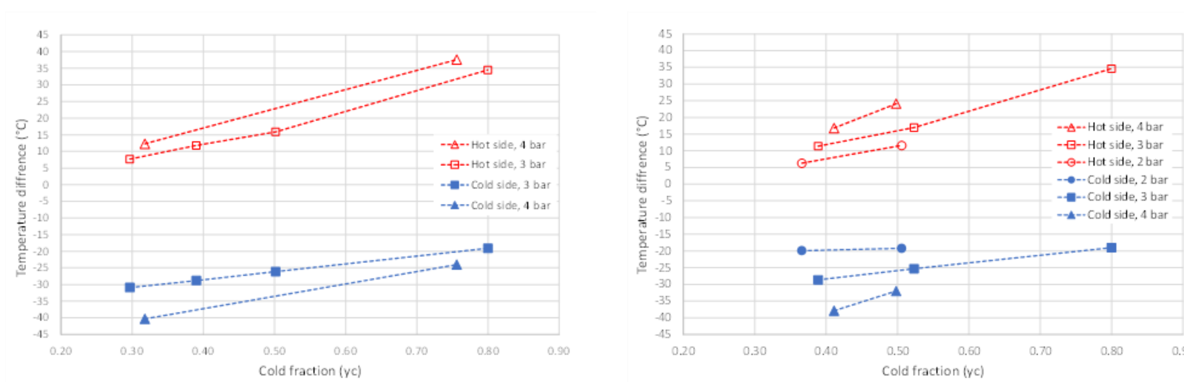


Figure 4- Temperature difference effect for the vortex separator at 2, 3, and 4 bar.

Computational Fluid Dynamics (CFD) Analysis & Optimization

To better understand the vortex separator's behavior and optimize performance, CFD simulations were conducted using OpenFoam®. These models accurately capture gas flow dynamics, CO_2 separation, and temperature effects, aligning with experimental data.

Initial CFD results indicate CO_2 concentrates in the cold stream, achieving a projected 80% separation under certain conditions. The model also predicts a cooling capacity of ~8°C and a heating capacity of ~22°C. CFD studies have highlighted that pressure and temperature gradients significantly impact separation efficiency.

Further optimization efforts focus on refining operating conditions (e.g., inlet pressure, mass flow rates, and temperature) and geometric design (e.g., nozzle diameter, angle, and tube length). The insights from CFD will guide the next phase of experimental testing to improve the vortex generator's CO_2 capture efficiency and cooling potential.

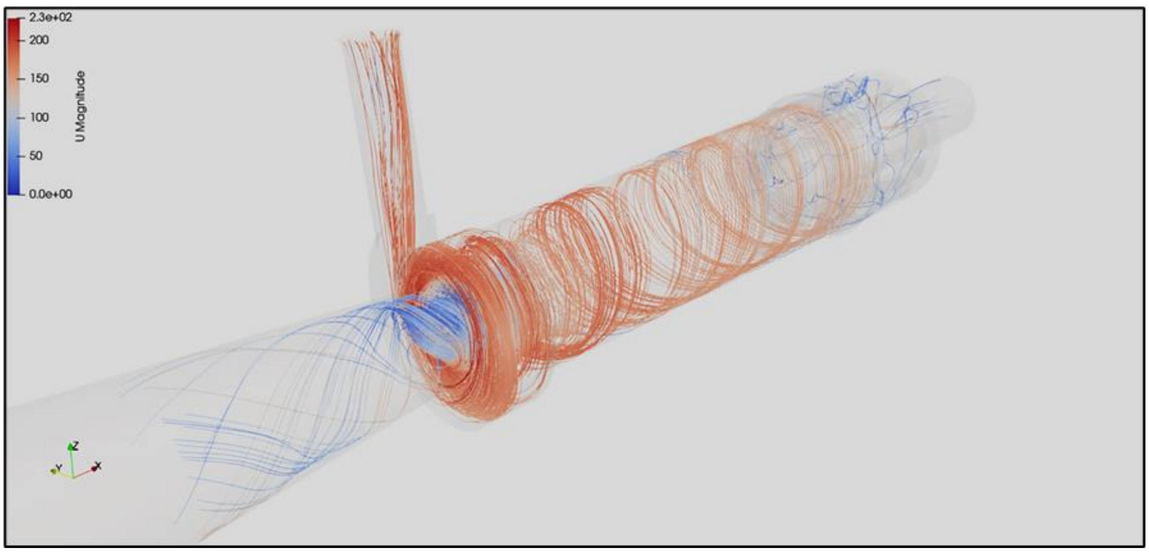


Figure 5- Velocity profile (U, m/s) for the vortex separator using a 0.4 %vol.CO_2/N2 feed.

Milestone #2 - Optimize bench-prototype design for flue gas post-combustion capture at 16 kgCO_2/day.

Task Description	Deliverable
2.1. Implement design modifications into SDS	
2.2. Run modified prototype (beta) with flue gas	
2.3. Compare results with CFD simulations and analyze	Testing report and data analysis

Optimization – Vortex separator as an Upstream Concentrator

Based on the performance of the vortex separator as a standalone capture device the performance of a vortex-based separation system for CO_2 capture and its integration with adsorption and heat recovery technologies was undertaken. The vortex separator demonstrated separation efficiencies of up to 45% CO_2 and cooling capacities of up to -40°C. A new process configuration integrating vortex separation with adsorption was proposed, aiming to reduce energy consumption by over 60% compared to traditional technologies.

Experimental results of CO_2 adsorption at sub-ambient temperatures using a Zeolite sorbent showed adsorption capacities between 2-4.5 mmolCO_2/g sorbent, with better performance at lower temperatures. Challenges in equipment sensitivity and sorbent regeneration were noted, suggesting further research to optimize the operation.

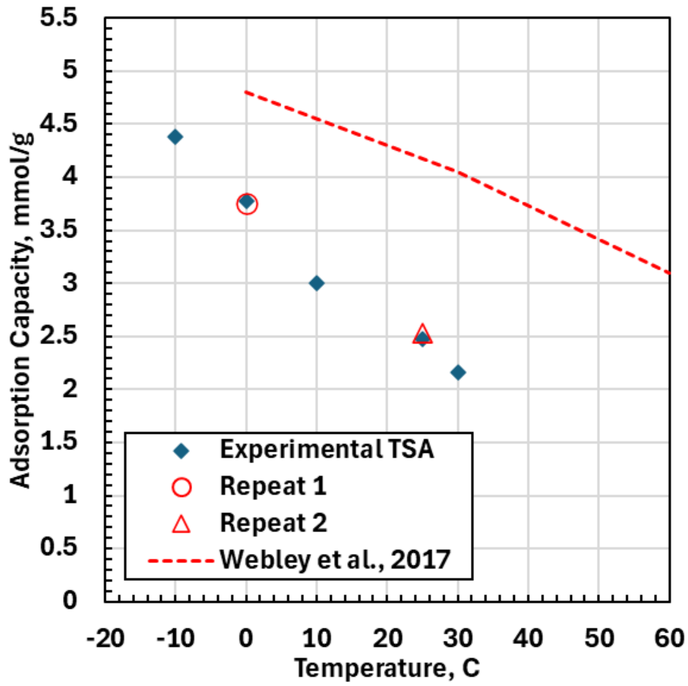


Figure 6- Adsorption capacity of the solid sorbent at different temperatures.

Modelling of Temperature Vacuum-Swing Adsorption (TVSA) to reduce energy use during sorbent regeneration was also investigated. Simulations indicated that while energy requirements were higher at lower temperatures, the adsorption capacity of Zeolite increased at sub-ambient conditions. TVSA simulations revealed that heating accounted for 70% of energy requirements, with total energy use ranging from 1.89 to 1.96 GJ/tCO_2.

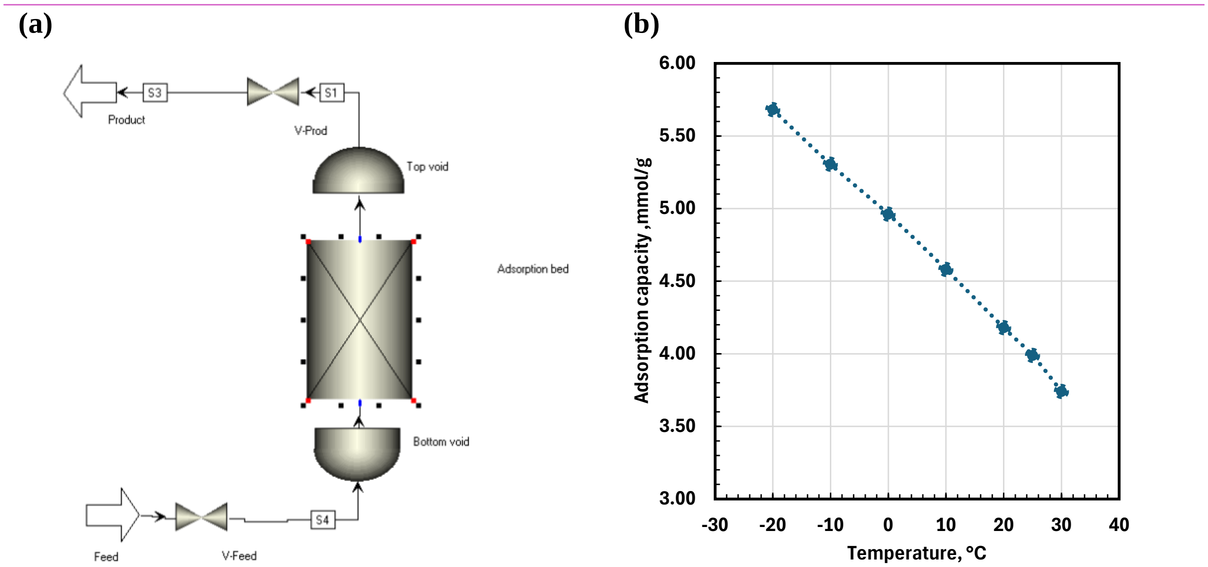


Figure 7- (a) Adsorption column simulation, ASPEN Adsorption V.14, and (b) adsorption capacity resulted at different temperatures.

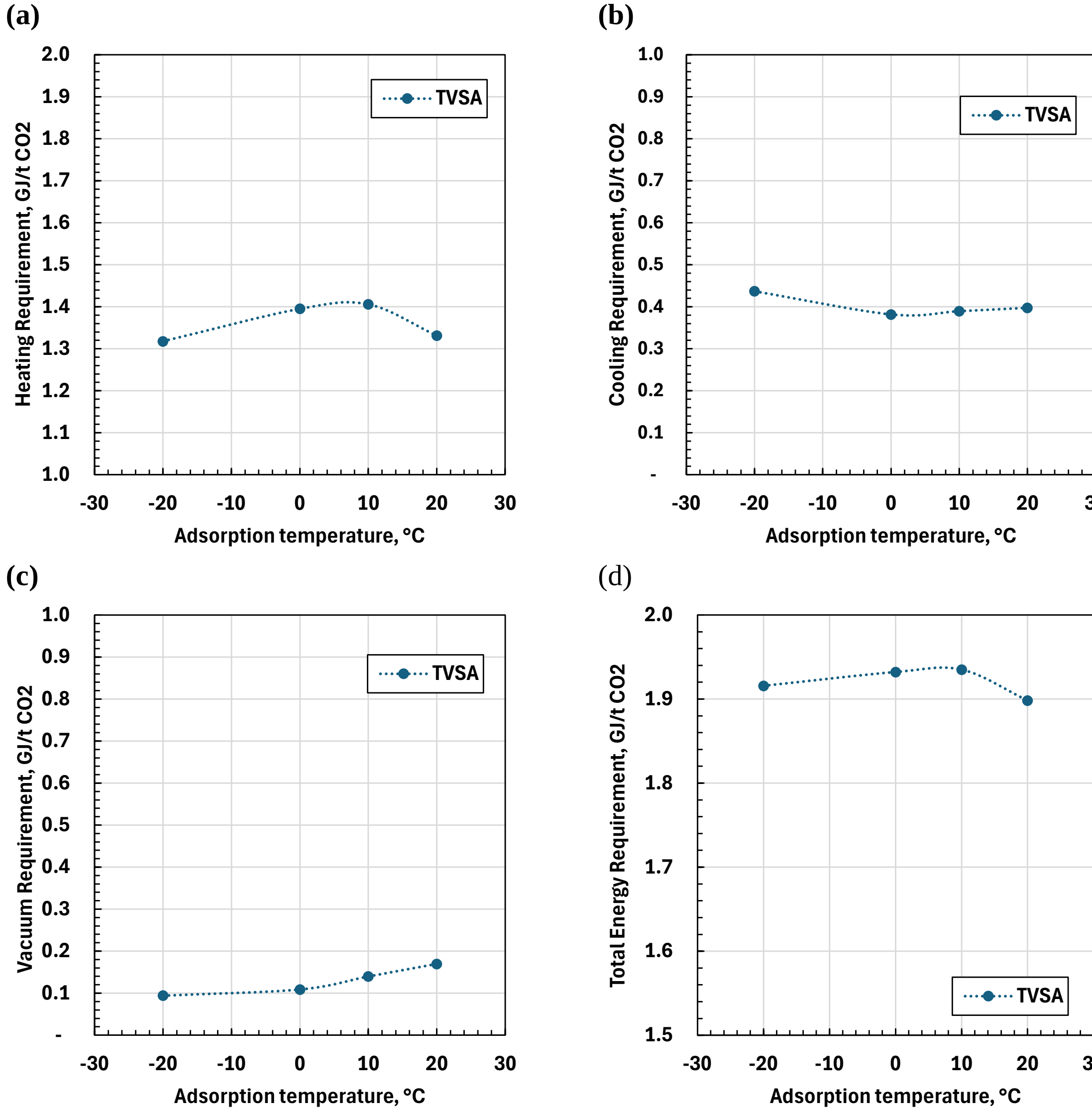


Figure 8- Energy duty estimate for utility on the TVSA cycle: (a) heating, (b) cooling, (c) vacuum, and (d) total energy duty.

Technical Economic Feasibility

A preliminary techno-economic analysis was conducted for a CO_2 capture capacity of 1 million tonnes per year. The estimated capture costs varied significantly with heat recovery efficiency: 48 $/t$CO_2$ for 100% recovery, rising to 86 $/t$CO_2$ and 134 $/t$CO_2$ for 80% and 50% recovery, respectively. The analysis showed that heat recovery efficiency strongly impacts both capture costs and emissions profiles. The proposed process demonstrated lower emissions (28 kgCO_2/tCO_2 for 100% recovery) compared to traditional amine-based systems, which emit 502 kgCO_2/tCO_2.

Table 4- Indicator summary for CO_2 cost of capture estimation.

Scenario for heat recovery	(1) 100% recovery		(2) 80% recovery		(3) 50% recovery	
Cost Component	% of total	\$/t of CO_2	% of total	\$/t of CO_2	% of total	\$/t of CO_2
Capital-Related Costs	55.8%	\$26.5	35.9%	\$30.9	25.1%	\$33.7
Decommissioning Costs	0.4%	\$0.2	0.2%	\$0.2	0.2%	\$0.2
Fixed O&M	24.9%	\$11.8	15.7%	\$13.5	10.8%	\$14.5
Feedstock Costs	0.0%	\$0.0	0.0%	\$0.0	0.0%	\$0.0
Other Raw Material Costs	0.0%	\$0.0	0.0%	\$0.0	0.0%	\$0.0
Byproduct Credits	0.0%	\$0.0	0.0%	\$0.0	0.0%	\$0.0
Other Variable Costs (including utilities)	19.0%	\$9.0	48.2%	\$41.5	64.0%	\$86.0
Total capture costs		\$47.5		\$86.1		\$134.3
Climate contribution						
Emissions ($kgCO_2/tCO_{2\ captured}$)		28		118		230
CO_2 removal efficiency (%)		97		88		77

Key Takeaways

In conclusion, the vortex-adsorption system shows promising potential for CO_2 capture with competitive cost and performance compared to conventional methods. However, the efficiency of heat recovery is a critical factor, and further refinement of the cost and energy assumptions is necessary for accurate cost projections and performance improvements. The next steps involve collaborating with engineering experts to refine the assumptions and improve the system's overall efficiency.

Milestone 3 - Validate gas separation principles on CFD model from experimental data.

Task Description	Deliverable
3.1. Evaluate input data from experiments.	
3.2. Develop a CFD simulation plan and execute it aligned with experimental data obtained (design, operating conditions, others)	
3.3. Validate model predictions with real data obtained from experiments.	CFD model validation report from laboratory experiments
3.4. Develop design basis for 100 kg/day laboratory pilot	Design basis for laboratory pilot

Methodology

A customized numerical solver was developed for the vortex tube simulations using OpenFOAM (OF) v7, an open-source finite-volume CFD package. This solver, named rhoReactingFoamPTDM, is an extension of the original rhoReactingFoam solver (OpenFOAM Repository, 2023) (Kadar, 2015) (Keenan, 2017). It is designed to simulate transient, compressible, multi-species, viscous mixture flows under non-reacting, turbulent conditions.

Since rhoReactingFoamPTDM is primarily intended for modeling species separation in flue gas mixtures, particular emphasis is placed on accurately capturing inter-species mass diffusion processes and the parameters governing species separation. To enhance its capabilities, the following modifications have been implemented:

- Energy Exchange Due to Mass Diffusion: An additional term is incorporated into the energy conservation equation to account for energy transfer between species via mass diffusion, following (Kelm, 2021) (Kumar, 2019).

- Mass Fraction Conservation Enhancement: The mass fraction conservation equation is re-derived based on (Ghazanfari, 2022) to incorporate temperature- and pressure-driven mass diffusion, in addition to shear and viscous diffusion.

Simulation Setup

The simulation setup for the vortex tube was structured into computational domain definition, boundary conditions, and numerical schemes.

Computational Domain

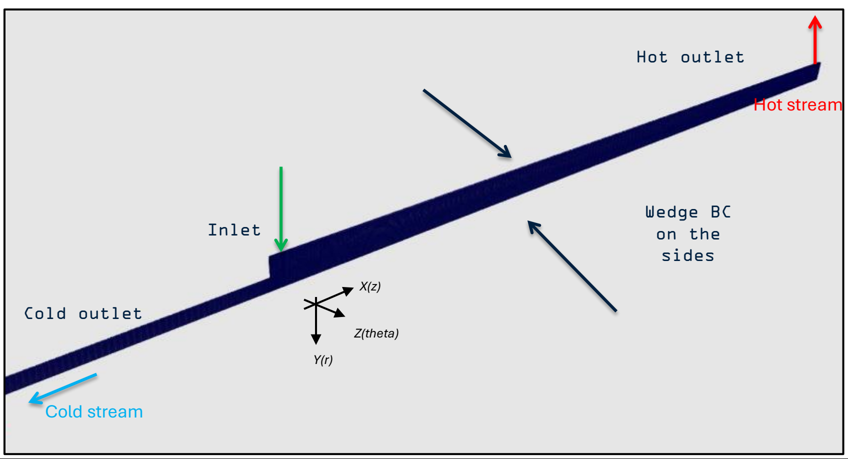
- A 2D axisymmetric wedge model of the vortex generator was used to replicate the actual geometry. The computational domain was meshed using a structured grid with 48,124 hexahedral cells, chosen based on a mesh dependence study. Near-wall regions are refined to capture turbulence accurately, ensuring compatibility with the RNG k-ε turbulence model.

Operating and Boundary Conditions

- The operating fluid was a CO_2-N_2 flue gas mixture (4% CO_2, 96% N_2), with inlet conditions set at 2.10 bar pressure, 298 K temperature, and velocity components designed to match experimental data. Ideal gas law was used to model thermodynamic properties, validated against the Peng-Robinson EoS with minor deviations. Boundary conditions include fixed pressure at inlets and outlets, with a specified volumetric flow rate at the cold outlet.

Numerical Schemes

- The governing equations are solved using finite volume integration with a PIMPLE algorithm, which combines PISO and SIMPLE methods for pressure-velocity coupling. Second-order spatial and temporal discretization ensures solution accuracy. Convergence is achieved within 0.018–0.022 s of flow time, requiring 18–22 hours of computation on a 32-core HPC system.



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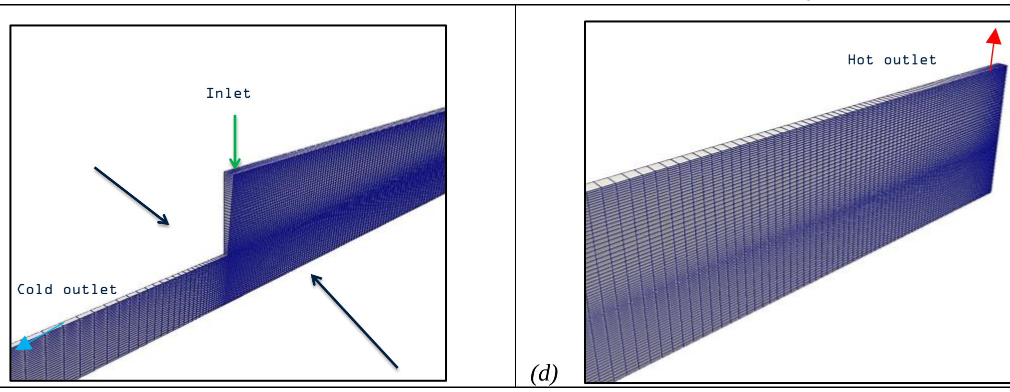

Figure 9- Overall view of actual geometry of vortex tube VORTEX GENERATOR from the Catalogue (a); computational domain of LVT with the generated mesh in isometric (b) and close-up (c-d) views. Note the location of inlet, and the hot/cold -e

Model Validation

The rhoReactingFoamPTDM solver was validated against experimental data and the vortex generator Catalogue using the LVT simulation model. Simulations were conducted under baseline conditions, ensuring consistency with reference data. The model was tested for varying hot-end pressures (1.10–1.85 bar), replicating experimental adjustments.

Cooling and heating performance were assessed using dimensionless temperature differences, revealing trends consistent with experimental and catalogue data. The CFD model captured the quasi-linear decline in cooling ($[\Delta T_{ic}/\Delta T_{ic_{max}}]$) with increasing cold fraction (ycy_cyc), while heating ($[\Delta T_{hi}/\Delta T_{hi_{max}}$) followed the reverse trend. The best agreement was observed between CFD and the catalogue, while experimental uncertainties led to deviations of 10-15%.

CO_2 separation efficiency showed a bowl-shaped trend, with maximum separation (51.87%) at yc=0.27y_c = 0.27yc=0.27 and a minimum (6.11%) at yc=0.54y_c = 0.54yc=0.54. The behavior aligned with experimental results, confirming the model's ability to replicate gas separation mechanisms.

Flow field analysis showed the formation of primary (free) and secondary (forced) vortices, driving energy separation via shear-induced mechanical work. CO_2 accumulation near the hot-end confirmed mass diffusion driven by temperature and pressure gradients.

Despite minor deviations (~13.78–18.21%) due to geometric simplifications, input uncertainties, and numerical errors, the solver accurately replicated experimental trends. The validated model is considered reliable for further parametric studies on the vortex separator vortex tube.

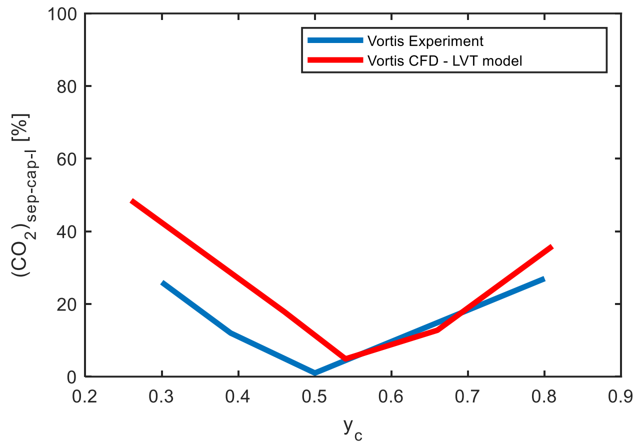

Figure 10- Comparison of LVT CO_2 separation capacity 〖"CO_2" 〗_" sep-cap-I" found from CFD vs experiment. Note that inlet total pressure of tube in simulation is pin-tot = 3.16 bar; experimental data are reported for pin-tot = 3.0 bar. CFD results are ex

Parametric simulation study

A parametric simulation study was conducted for the VORTEX SEPARATOR to characterize its performance maps, and ultimately suggest optimization strategies could improve its CO_2 separation capacity. The following variables were analyzed;

- Heating level (ΔThi)
- Cooling level (ΔTic)
- Isentropic efficiency (ζ_"s-c" /ζ_"s-h")
- Coefficient of performance (〖"COP" 〗 _"c")
- Cooling margin (ΔTcb)
- Net percent CO_2 separation (〖"CO_2" 〗 _" sep-cap-I")
- Actual CO_2 separation (〖"CO_2" 〗 _" sep-cap-II")

The findings suggest that the vortex separator can efficiently separate CO_2, and the insights will guide the development of an integrated vortex-adsorption process at pilot scale.

Key Learnings

Milestone #1 – Test Bench Scale Prototype with Flue Gas Mix

Lessons Learned:

- The initial prototype produced strong vortices but insufficient residence time for sustained separation. The design was modified to create strong and sustained vortices for better separation.
- The improved prototype achieved separation capacities of up to 45% CO_2 and cooling capacities down to -40°C under tested conditions, but its performance is influenced by operating factors, particularly pressure profiles within the unit. The separation capacity also did not meet the minimum commercially viable threshold of 95%.
- The cooling capacity of the separator presents an opportunity for improving process efficiency by utilizing its low-cost cooling and heating streams for downstream polishing, which could improve CO_2 capture at lower energy consumption and cost.
- A new process integrating vortex separation and adsorption has been proposed, which is expected to reduce energy use by over 60% compared to existing post-combustion capture technologies. Ongoing work includes developing a process model and performing a techno-economic analysis to refine energy use and capture cost predictions for this integrated process.

Milestone #2 - Optimize bench-prototype design for flue gas post-combustion capture at 16 $kgCO_2$/day.

Lessons Learned:

- An optimized process configuration was identified, which integrated the vortex separator with a downstream absorption system, exceeding key performance metrics in capture efficiency, energy use, and cost-effectiveness. This design basis demonstrated an increase in separation capacity to over 90% CO_2 using the vortex separator's cooling and heating capabilities.
- TEA informed by experimental and modeling data, revealing costs ranging from 48 $/ton CO_2 to 134 $/ton CO_2 based on various heat recovery assumptions.
- Experimental data was used to validate the CFD model, supporting future optimization tasks in Milestone #3.

Milestone 3 - Validate gas separation principles on CFD model from experimental data.

Lessons learned:

- A CFD model was developed to optimize Vortis's carbon capture prototype, specifically focusing on vortex tubes for CO_2 separation. The model, validated against experimental data from the vortex separator, identified key design variables affecting CO_2 separation: inlet pressure, temperature, CO_2 content, radial velocity, and cold-end flow rate. Parametric studies showed that optimal conditions improve both cooling and CO_2 separation. Future work includes using machine learning for further optimization and incorporating geometrical design variables. The findings suggest that the vortex separator can efficiently separate CO_2, and the insights will guide the development of an integrated vortex-adsorption process at pilot scale.

Outcomes and Impact

Table 1 Clean Resources Metrics

Metric	Project Target	Commercialization / Mobilization Target	Project Impact to Metric
Investment in 4 Core Strategic Technology Areas	Develop one (1) Clean Technology for Carbon Capture	Develop a modular, electric, high-efficiency carbon capture technology for gas compression stations. Engage with industrial user for development partnerships	Throughout the course of the project, Vortis has successfully developed two bench-scale prototypes, the "alpha" and "beta" models, for its mechanical separation technology aimed at CO_2 capture. With the support of Vortis NGIF funding, we have engaged with several industrial end users to gather valuable feedback on the development and design of our capture technology. This collaboration has been instrumental in refining the technology to meet the needs of the industry.
TRL advancement	Progress from TRL 3 to TRL5	Initiate laboratory testing and integrate partner for pilot development	At the conclusion of this project. Vortis has the data and design basis to proceed to laboratory pilot evaluating the TRL readiness to 5.
Future Capital Investment	If successful the next step of the development may bring to Alberta over $7 million in capital investment.	Work with user partnership and VCs to obtain the necessary capital	Omitted due to confidentiality.

Field pilots/demonstrations	Develop design for one (1) pilot unit design	Work with an engineering partner in the design development based on the project's results	A preliminary design basis has been developed during this project for 100 kg/day laboratory pilot.
Collaborators	Continue collaboration with three (3) partners, including UBC, Nanostech, and engineering company, for the design and manufacturing of prototype and pilot units	Maintain and manage collaborations via regular meetings and results sharing	Continued collaboration was maintained throughout the project and is expected to continue after the conclusion of this project.
Publications	Publish one (1) article on a peer-review journal	Article already on the go, journal identified, waiting from laboratory results to finalize the submissions	One published article was withheld as new IP was secured.
Knowledge Mobilization	Attendance to two (2) conferences and trade shows \to showcase the project achievements	Select proper venues to present project results and prepare material for presentation	No attendance was recorded during this project
Students Trained (M.Sc., Ph.D., Postdoc)	Train two (2) student during the excecution of the project	Work with UBC in applying for NSERC grant to hire students before the project starts	During the project Vortis utilized two M.Sc students for the associated experimental and process modeling work.
Sector HQP Trained	Train two (2) new HQP on new technologies for Carbon Capture	Look to hire staff as needed to achieve the project's goals	Vortis achieved training two new HQP personnel
Existing Sector HQP Jobs Retained	Retain three (3) HQP on new technologies for Carbon Capture	Provide our staff with the proper conditions for effective work and connect the work with a longer-term vision associated with decarbonizing our economy	Vortis retained less than 3 full time HQP at the closure of this project.

Jobs: Actual new jobs created from project	Create over 30 full-time high skilled jobs in Alberta for the commercial scale-up of the SDS including the design, build, and operation of future laboratory pilots, and commercial demonstrations.	Establish a scale-up strategy to define best pathway to market access and talent acquisition	Based on the conclusions from the experimental and analytical data Vortis believes this metric is attainable for the scale up of this technology.
GHG emissions: Projected reductions from future deployment (to 2030)	Reduce Alberta's emissions by 8 MtCO_2eq/year through commercial deployment by 2030	Engage with users during the project to look for development and implementation agreements with industrial partners	Based on the conclusions from the experimental and analytical data Vortis believes this metric is attainable for the scale up of this technology.

Table 2 Program-Specific Metrics

GHG emissions: Actual reductions from project	Project Target	Commercialization / Mobilization Target	Comments (as needed)
# of alternative energy technologies deployed	Develop one (1) Clean Technology for Carbon Capture	Develop a modular, electric, high-efficiency carbon capture technology for gas compression stations. Engage with industrial user for development partnerships	At the conclusion of this project, Vortis demonstrated a bench-scale carbon capture technology that has potential applications for a number of point source emissions.
$ intensity cost reduction on production of CO_2	Reduce cost of CO_2 capture by 50%	Monitor technology for energy and cost reduction with respect to incumbent CO_2 capture technologies	At the conclusion of this project Vortis has demonstrated preliminary results with an optimized process design of the technology to achieve CO_2 capture reduction in excess of 50%

Table 3 - Project Success Metrics

Metric	Project Target	Commercialization / Mobilization Target	Comments (as needed)
Capture efficiency	Beta prototype is achieving 76% or more of capture efficiency for flue gas feed	Measure capture efficiency, identify ways of improving performance if needed	The optimized bench scale prototype has the potential to achieve beyond 90% capture efficiency at scale.
CO_2 purity	The CO_2 purity in the product stream is above 96 vol%	Measure CO_2 purity, identify ways to improve performance if needed	The optimized bench scale prototype has the potential to achieve beyond 96% vol CO_2 purity at scale.
Energy use	The energy use per tonne of CO_2 capture is in the range of 20-40 kWh/tonneCO_2	Monitor energy consumption and extrapolate to industrial capacity based on prototype performance. Identify ways to improve performance if needed	Process modelling of the optimized bench-scale model demonstrated the potential to achieve below 1 GJ/ tonneCO_2
CFD model uncertainty	CFD model projections below a 5% deviation from the experimental data	Validate model results with experimental data. Optimize model parameters to achieve a good fit to experimental data	CFD model showed a deviation beyond 5%.

Benefits

Economic

The R&D and commercial deployment of the SDS process are expected to have significant economic impacts to the province of Alberta. Including increased economic activity, job creation, competitiveness, and investment attractiveness.

At full commercial scale, the SDS process has the potential to transform Alberta's oil and gas industry and economy. Delivering low-cost carbon removal technologies will enable Alberta's oil and gas sector to cost-effectively eliminate their emissions associated with oil and gas production, making the industry cleaner and more competitive at a global scale. As the world move towards net-zero, policies such as the carbon tax create new costs and liabilities for Alberta. The SDS process provides a low-cost solution for emitters to lower their costs and liabilities associated with their emissions. The deployment of the SDS at scale will also create hundreds of thousands of temporary and full-time jobs, and reducing emissions and increasing competitiveness of Alberta's oil and gas sector will also make the Alberta economy more competitive and resilient as the world transitions to net-zero. This enables the province to maintain and grow oil and gas revenues, GDP, and standard of living for all Albertans. In addition, a cleaner, more competitive oil and gas industry will also increase the investment attractiveness of the industry and province, which will provide additional jobs, revenue, and prosperity for the province.

Environmental

Most notably, the SDS process promises to deliver a low-cost method for emitters to reduce carbon emissions. Alberta is the second largest emitter in Canada, with 256.4 megatonnes (MT) of carbon dioxide equivalent (CO_2e) in 2020. The oil and gas sector accounts for 52% of Alberta's annual emissions. Alberta's electricity grid produces more GHG emissions than any other province, with an average carbon intensity of 590 grams of CO_2e per kilowatt-hour (g CO_2e per kWh)2. Alberta's Emissions Reduction and Energy Development Plan illustrates an aspirational pathway to carbon neutrality by 2050 without compromising affordable, reliable and secure energy for Albertans, Canadians and the world. The SDS process can be a valuable tool for Alberta to reduce emissions and achieve their emission reduction goals. In a broader context, SDS has the potential to address several of the United Nations stated sustainability development goals, including; affordable clean energy, climate action, decent work and economic work, among others. The proposed project will see minimal environmental benefits but will set the stage for the potential to reduce Alberta's emissions at a commercial scale drastically. The bench-scale prototype constructed in 2023 will have a 16kg/day capture capacity. This prototype will inform the development of a laboratory pilot with a 100 kg/day capture capacity in 2024 and a field pilot with a 1 tonne/day capture capacity. Each SDS module will have a capture capacity of 50 – 500 tonnes per day at the commercial scale. We believe by 2050, the SDS can make a significant impact in reducing emissions from the oil and gas sector and electricity generation, bringing Alberta closer to its net zero goal.

Building Innovation Capacity

The development of the SDS process within Alberta will also help to nurture a knowledge base and promote CCUS expertise within Alberta. Given the advanced molecular separation principles and highly technical operational parameters of the SDS process, commercialization and advancements in the technology will require significant training, qualification of highly specialized resources, and knowledge development for trades, professionals, and management. During the project and subsequent scale-up and commercialization of the SDS, Vortis will work closely with the University of Calgary's emission testing centre (ETC) and Vortis is well-positioned to transfer knowledge to numerous researchers and engineers. As the technology advances, further knowledge transfer will occur with technology adopters through licensing. The project also intends to publish several academic and industry papers to raise awareness within the industry and academia of mechanical gas separation. This has the potential to spark innovations within this field that can have far-reaching benefits to numerous untold industries within Alberta. In addition, because the SDS process drives down the cost of capture, this will directly benefit utilization technologies enabling them to access cheaper, more efficient CO_2 feedstock for conversion into carbon-neutral products

Recommendations and Next Steps

Vortis is a carbon management company focused on creating a platform that enables emitters to effectively mitigate and monetize their carbon emissions. We offer a comprehensive solution for capturing, converting, and monetizing carbon emissions, starting with accessible and affordable capture technologies. In the short term, our primary opportunity lies in helping natural gas industry emitters capture and sequester their carbon emissions in a cost-effective and straightforward manner. Over the long term, we see greater value in converting CO_2 into valuable products such as fuels, plastics, and carbon-based materials, offering significant monetization potential for our customers.

Based on the results of this project, Vortis plans to collaborate closely with industrial partners to explore potential integration options for the vortex separator, either as a standalone capture system or as part of an integrated process. Once a specific customer and application are identified, we will develop a tailored pilot and scaling strategy.

Knowledge Dissemination

Additional pilot operations are necessary to confirm the projected economic and environmental benefits. If these operations prove to be technically and economically viable, the findings will be shared through standard project disclosure channels, including Alberta Innovates and NRCan. Vortis will also provide non-proprietary information through the NGIF, Pathways consortium, and other industry-led groups. In addition, Vortis will promote awareness of the process through its regular marketing and communications efforts.

Conclusions

In collaboration with the University of British Columbia, the Natural Gas Innovation Fund, and NanosTech, Vortis aims to reduce the costs and liabilities associated with carbon emission mitigation in oil and gas production. The proposed work focused on optimizing and testing Vortis's SDS at a bench scale to evaluate its commercial viability and prepare for a 100 kg/day laboratory pilot.

The project objectives included:

1. Test the SDS at a bench scale using a simulated flue gas mix.
2. Identify design improvements and validate them through computational fluid dynamics (CFD) simulations.
3. Implement the revised design improvements and evaluate SDS performance using real flue gas at a bench scale.
4. Develop a design basis for the laboratory pilot and prepare an economic and technical feasibility report.

The project provided several key insights. Notably, the initial design of the vortex separator was found to be unviable, as the residence time of the vortices could not be maintained for an adequate duration. However, subsequent design revisions and process integrations with conventional carbon capture systems produced promising results and provided a design basis for further investigation via a pilot.