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Characteristics of Carbon Dioxide Separation from Air-CO_2 Mixture by Narrow Nozzle Vortex Tube under Low Pressures

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***Abstract* -** This study presents carbon dioxide separation from an air-CO_2 mixture utilizing a vortex tube energy device at 4 and 5-bar_g pressures. Since the vortex tube reduces the temperature of the gas mixture at the cold gas exit, the vertically standing vortex tube with a bottom-side cold gas exit exhausts the CO_2-rich gas mixture. As the inlet pressure is increased from 4 bar_g to 5 bar_g, the nozzle exit temperature of the CO_2-air mixture is lowered at the cold gas exit temperature and raised at the hot gas exit temperature. The colder gas increases the separation percentage of CO_2 from the air-CO_2 mixture. Results show that the percent CO_2 separation at 20% cold mass fraction is increased from 15.5% to 17.5% with a pressure increase of 4 to 5 bar_g.

***Keywords*:** Vortex tube, Temperature separation, CO_2 capture, Species separation.

1. Introduction

Science has shown that human-generated greenhouse gases, such as carbon dioxide, influence the overall extent of global warming. Reducing greenhouse gas emissions is essential for preventing catastrophic climate change. This issue requires enhancing carbon absorption through carbon capture and storage (CCS) technology [1].

Carbon Capture and Storage (CCS) consists of three primary stages: capture, transport, and storage. In the storage stage, the post-combustion capture method is particularly notable for separating CO_2 from exhaust gases generated after fuel combustion, such as coal, oil, and natural gas. The method includes chemical absorption using amine solvents (MEA, DEA, MDEA) to absorb CO_2; adsorption using solid materials like activated carbon, zeolite, and MOFs to trap CO_2, and membrane separation using polymer membranes to filter CO_2 from exhaust gas mixtures. These solutions are easily applicable to existing plants. However, they consume significant energy for solvent regeneration, incur high operational costs, cause equipment corrosion, and produce secondary waste. Therefore, an alternative method is actively being researched to overcome the drawbacks of these methods in CO_2 capture [2].

This study investigates the vortex tube device, a gas separation method with substantial application potential. This device can separate an incoming compressed gas stream into hot and cold gas streams without inducing chemical reactions or combustion. Additionally, it offers a simple design, rapid cooling, environmental sustainability, and greater cost-effectiveness compared to alternative methods.

Numerous scientists have investigated the vortex tube using numerical approaches, simulations, computations, and experiments. Xiangji Guo[3] analyzed the unsteady heat and mass transfer processes in a Ranque–Hilsch vortex tube. Yunpeng Xue [4] investigated the flow characteristics within a vortex tube with different configurations. Abbas Moraveji [5] simulated the heat transfer and fluid flow characteristics in a vortex tube using computational fluid dynamics by considering the various parameters. Hitesh R. Thakare [6] conducted an experimental investigation and performed CFD analysis of the Ranque–Hilsch vortex tube. Mohammad O. Hamdan [7] conducted an experimental vortex tube energy separation study under different tube designs. K. Kiran Kumar Rao [8] performed a CFD simulation to determine the optimum material for fabricating the counter flow of the Ranque–Hilsch vortex tube.

This experiment investigates the temperature and CO_2 separation efficiency of the air-CO_2 gas mixture under various inlet conditions of 4 and 5 bar pressure at 20 °C. The results indicate that, for an inlet pressure of 5 bar, a more significant temperature and CO_2 separation is achieved than an inlet pressure of 4 bar. These findings endorse the formulation of sustainable CO_2 management systems, particularly for low-temperature gas processing applications.

2. Experimental methodology

2.1. Experimental apparatus

Figure 1 depicts an experimental configuration. Compressed air from the compressor flows into the vortex tube via the inlet. Carbon dioxide gas is contained in a CO_2 cylinder. The air and CO_2 streams are regulated by a pressure regulator and a mass flow controller to maintain a steady flow rate; afterward, the CO_2 gas is mixed with compressed air in the mixing chamber and directed into the vortex tube through the generator, creating a swirling flow. This motion results in the separation of gases into hot and cold streams. The heated gas migrates to the periphery of the vortex tube and is expelled by the hot outlet, whilst the cooled gas converges towards the center and is discharged through the cold outlet.

Thermocouples and pressure sensors are positioned at the inlet, hot, and cold outlets to measure the gas streams. Mass flow meters (MFM) quantify the cold outlet's flow rates. The sensors are gathered and observed using a computer with graph plotting software, enabling researchers to evaluate the vortex tube's performance under varying situations.

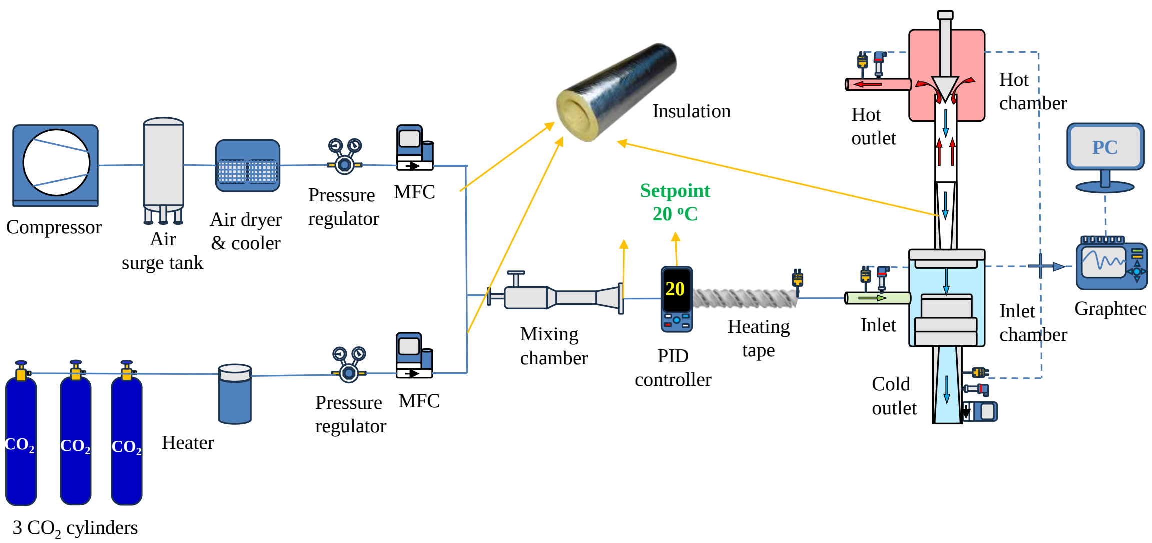


Figure 1. The diagram of the vortex tube system

2.2. Experimental procedures and definitions of variables

To determine the pressure at the inlet, the throttle valve is fully closed, and air is poured into the system. To ensure minimal error, all equipment is calibrated before the experiment, and the CO_2 gas chosen has a purity of 99.9%. The gas mixture is introduced into the vortex tube system for 2700 seconds to allow the temperature to reach a steady state. Sensors measure pressure and temperature, an MFC controls the mass flow rate, and an MRU chromatographer measures the CO_2 concentration percentage. All of these parameters are recorded on a computer throughout the experiment.

Table 1. Inlet conditions of the vortex tube

Parameter	Value	Unit
P_{inlet}	4 and 5	bar
T_{inlet}	20	°C
Mass fraction of CO_2 to air	20	%
Cold mass flow ratio y_c	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8	-

Table 1 shows the input operating conditions of the vortex tube system. Where cold mass flow ratio y_c is defined as the cold outlet's mass flow rate divided by the inlet's mass flow rate.

$$y_c = \frac{\dot{m}_c}{\dot{m}_\iota} \tag{1}$$

where:
$\dot{y}_c$ – Cold mass flow ratio
$\dot{m}_c$ – Mass flow rate at the cold outlet (kg/s)
$\dot{m}_i$ – Mass flow rate at the inlet (kg/s)

In this study, all input conditions such as pressure, temperature, volumetric flow rate, and mass flow rate are kept constant, except for the y_c, which varies from 0.2 to 0.8, to investigate the outlets' temperature and CO2 separation efficiency.
When CO_2 gas is separated from the mixture, the mass flow rate of CO_2 should increase at the outlet. The percentage of CO_2 separation at the cold outlet of the vortex tube is defined as:

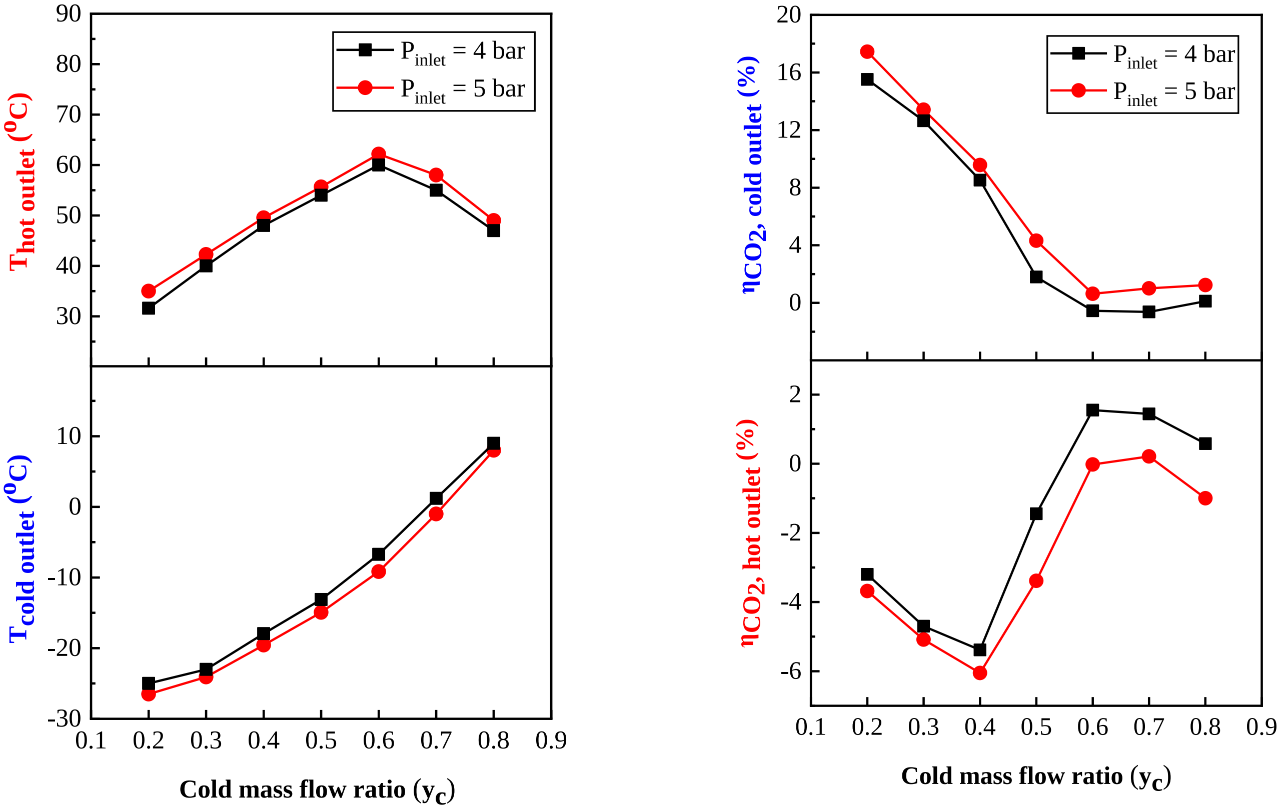
$$\eta_{CO_2} = \frac{\dot{m}_{CO_2,measured} - \dot{m}_{CO_{2,theoretical}}}{\dot{m}_{CO_{2,theoretical}}} \times 100 \tag{2}$$

where:
η_{CO_2} – The percentage of CO_2 separation at the cold outlet (%)
$\dot{m}_{CO2,measured}$ – Measured mass flow rate of CO_2 at the cold outlet (kg/s)
$\dot{m}_{CO2,theoretical}$ – Theoretical mass flow rate of CO_2 at the cold outlet (kg/s)

3. Results and discussion

Figure 2a) illustrates the temperature separation of the air-CO_2 gas mixture at the cold outlet. The results show that, at 5 bar inlet pressure, temperature separation is better than at 4 bar. At an inlet pressure of 5 bar, the cold outlet temperature reaches a minimum of -26.5°C at y_c=0.2, then gradually increases to 8.1°C at y_c=0.8. Besides, the hot outlet temperature is lowest at 35°C at y_c=0.2, peaks at 62.16 °C at y_c=0.6, and then decreases to 49.1 °C at y_c = 0.8. For an inlet pressure of 4 bar, the cold outlet temperature drops to a minimum of -24.98 °C at y_c=0.2, rising to 9.05 °C at y_c=0.8. The hot outlet temperature is minimal at 31.6°C at y_c=0.2, reaches a maximum of 60.1°C at y_c=0.6, and thereafter declines to 47°C at y_c=0.8. Figure 2b) presents the CO_2 separation efficiency at both the cold and hot outlets under pressures 4 and 5 bar. At y_c=0.2, the CO_2 separation efficiency reaches its maximum, 17.5% for an inlet pressure of 5 bar and 15.5% for 4 bar. As y_c increases, the efficiency declines sharply. The results demonstrate that higher inlet pressures of 5 bar lead to better temperature separation at the outlets compared to 4 bar.

A significant result is that the highest CO_2 separation efficiency at the cold outlet occurs at y_c=0.2, where the CO_2 temperature reaches its lowest point. This phenomenon can be explained by the difference in density between CO_2 and air. CO_2 has a higher molecular weight (44 g/mol) than air (approximately 29 g/mol on average). As the temperature decreases, air (primarily composed of N_2 and O_2) contracts more rapidly than CO_2, increasing the density difference. This effect leads to a higher concentration of CO_2 at the cold outlet [9].



a)

b)

Figure 2. Effect of the inlet pressure 4 bar and 5 bar on the temperature and CO_2 separation at the cold outlet a) Temperature separation at the cold outlet, b) CO_2 separation performance at the cold outlet

4. Conclusion

This study demonstrates that pressure plays a crucial role in the performance of the vortex tube. As the inlet pressure increases, the temperature and CO_2 separation efficiency significantly improves, particularly at the cold outlet. This result is a foundation for cooling CO_2 to its liquid phase, facilitating easier storage and reuse. Consequently, this method can be applied to carbon extraction from industrial emissions, contributing to reducing greenhouse gas emissions and alleviating climate change.

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