Oxygen separation in a vortex tube with applied magnetic field

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Abstract. The large scale and efficiency of air separation units remain key barriers towards modular, distributed liquid oxygen systems. Identifying new physical separation mechanisms, or novel combinations of established methods, could enable the development of smaller, more modular air separation systems. This paper investigates the combination of centrifugal separation with paramagnetism of liquid oxygen in a vortex tube. The magnetic field is applied via externally mounted 1.5-T bar magnets along the length of the periphery of the vortex tube. Calibrated air mixtures with 21.1-21.4% oxygen and the remainder nitrogen are tested. Inlet vortex tube fluid conditions are held between 89 and 90 K and 305-320 kPa and expanded to 162-286 kPa. Gas chromatography analysis on the calibrated air samples shows the magnetic field gradient on the vortex tube produces up to a 42.09% purity as opposed to 27.95% purity in identical trials without a gradient. Purity and yield are shown to be inversely related in the periphery and directly related in the core. The results indicate a potential to increase oxygen purity and yield in a more compact form factor.

1. Introduction

The cost of oxygen separation is a key barrier towards localized and efficient oxygen production which directly affects the aerospace and medical industries. Two major cost contributors are the low efficiency and large size of gravity-based cryogenic distillation columns that are used for separating oxygen from air. Transport of liquid oxygen is more economical than gaseous due to increase in product density without drastic increases in storage vessel cost. Oxygen is typically gathered in standard industrial distillation columns, which are typically 6-meters in diameter and 30-meters tall [1]. The implementation of vortex tubes could potentially result in a cost reduction. Previous works have investigated oxygen separation with non-magnetized vortex tubes [2-7] or with non-centrifugal magnetization schemes [8, 9]. A similar application of the combination of centrifugal and magnetic field gradients is applied in magnetogravimetric methods for mineral separation and has been successfully implemented in spinning centrifuges [10].

In this work a method to increase oxygen separation in a more compact form factor is explored. This is done by applying a magnetic field gradient within a counter-flow Ranque-Hilsch vortex tube with external bar magnets. A theoretical model is created to demonstrate the ability of the magnets to pull a drop of liquid oxygen to the edge of the vortex tube. Experimental trials with and without the magnets are tested with calibrated air. The oxygen separation is quantified relative to the calibrated air supply at both outlets of the vortex tube using randomized batch-type gas chromatography.

2. Theory

The vortex tube was first patented by Georges Ranque in 1933 for cooling and heating operations. Rudolf Hilsch later developed the modern counter-flow vortex tube shown in Figure 1. The vortex tube processes pressurized fluid as an input and uses solid-state tangential nozzles to generate a vortex. This promotes a high-shear environment near the wall of the tube producing a temperature gradient through enthalpy streaming. This effect has resulted in the intuitive “cold” outlet at Point 2 in Figure 1 and the “hot” outlet at Point 3. In this paper the nomenclature of “core” and “periphery” are used for specie separation applications.
First order calculations are made to determine whether the paramagnetism of oxygen is significant compared to the dominant centrifugal force within a vortex tube [12]. The centrifugal force is calculated using Equation 1:

\[ F_c = \frac{mv^2}{r} \]  

where \( F_c \) is the centrifugal force acting on the droplet, \( m \) is the mass of the droplet, \( v \) is the droplet's velocity, and \( r \) is the radial location of the droplet. The velocity is the non-dimensional angular value based on the Reynolds number multiplied by the non-dimensional value. The total magnetic force is calculated using Equation 2 [13]:

\[ F_{Tm} = \frac{\pi r_d^4}{2\mu_0} \frac{\chi}{(1+\chi)^2} \cdot B^2 \]  

where \( F_{Tm} \) is the total magnetic force acting on the droplet, \( r_d \) is the radius of the spherical oxygen droplet, \( \mu_0 \) is the permeability of free space, \( \chi \) is the volumetric magnetic susceptibility, and \( B \) is the magnetic flux. The magnetic force acting on the droplet considering position is calculated using Equation 3:

\[ F_m = F_{Tm} - F_{Tm} \cdot \left( \frac{r_i - r}{r_i} \right)^2 \]  

where \( F_m \) is the magnetic force acting on the droplet at a given radial position, \( r \) is the radial location, and \( r_i \) is the inner radius of the vortex tube. Figure 2 displays a parametric sweep of the magnetic and centrifugal forces on a 0.25 mm droplet with an inlet Mach number of 0.66 within a typical vortex tube of 6-mm internal centrifuge diameter as a function of the radial position.
This calculation indicates that the balance of forces on a liquid oxygen droplet promote flow towards the wall of the vortex tube and that the paramagnetism induced by a magnetic field gradient is significant for vortex tube diameters on the order of half a centimeter.

3. Experiment
An experiment is implemented that allows for oxygen separation through a vortex tube to be monitored both with and without an applied magnetic field gradient. The selected vortex tube is a counter-flow Vortec 106-2-H with a 4.216-mm internal diameter. Six 1.5-Tesla N52 rare-earth bar magnets with lengthwise poles are attached in a removable fashion with alternating polarity to the vortex tube with a 3D printed fixture. The fixture positions the magnets along the periphery of the vortex tube in a cone-shape such that the magnets are in contact at the entrance of the vortex tube centrifuge and held 3.59-mm from the end of the periphery outlet as shown in Figure 3.

![Vortex tube with mounted magnets.](image)

The experiment schematic is shown in Figure 4. The schematic begins with a pressurized bottle of calibrated air with 21.1-21.4% oxygen fraction (depending on the bottle) and balanced with nitrogen. This leads into a 3/8-inch copper tubing heat exchanger immersed in liquid nitrogen to precool the air before entering the vortex tube. Both outlets of the vortex tube lead into copper heat exchangers which increase the air temperature above cryogenic using flows of hot air. Following the mini-heat exchangers are Alicat Scientific Mass Flow Controllers (MCR-100SLPM-D/5M) used to control the cold fraction. After the mass flow controllers are sampling ports. The air samples are collected in 0.5-L Tedlar bags without changing the flow fraction. Three calibrated platinum RTDs, one at each port on the vortex tube, are connected to a Cryocon 24C to monitor the temperature. The instrument accuracies given by the manufacturer are shown in Table 1.

![Experiment Schematic](image)
Table 1. Total Instrument Accuracies

| Dimension          | Instrument                                      | Accuracy               |
|-------------------|------------------------------------------------|------------------------|
| Pressure          | CGA-590 Pressure Regulator                      | ±3.447 kPa             |
| Temperature       | Cryocon 24C                                     | ±0.005% of the reading |
|                   | Lakeshore PT-111 RTD                            | ±0.25 K                |
| Volumetric Flow   | Alicat Scientific Mass Flow Controller MCR-100SLPM-D/SM | ±0.8% of the reading ± 0.2 SLPM |
| Gas Analysis      | Varian CP-3800 Gas Chromatographer               | ±0.42%                 |

An inlet temperature for the vortex tube is determined prior to testing that will allow the oxygen to liquefy at entry. The boundary conditions are summarized in Table 2. At atmospheric pressure the bubble point for oxygen in this air mixture is 81.552 K. In this mixture oxygen becomes liquid at 310.264 kPa and 90.015 K. With an average Joule-Thompson coefficient of 0.0218 K/kPa and a change in pressure of 13.790 kPa the modified inlet temperature is 89.715 K [14].

Table 2. Test Boundary Conditions

| Condition               | Value                        |
|-------------------------|------------------------------|
| Vortex Tube Inlet Temperature | 89-90 ± 0.25 K               |
| Vortex Tube Inlet Pressure        | 305-320 ± 3.447 kPa          |
| Total Flow Rate          | 60 ± 0.68 SLPM               |
| System Back Pressure     | 162-286 ± 3.447 kPa         |

Cold fractions vary from 20-80% in increments of 15%. At each cold fraction eight gas samples are collected – four with an applied magnetic field and four without. Within each set of four samples, two are from either vortex tube outlet. The samples are collected in Tedlar bags and analyzed using gas chromatography relative to the calibrated supply air.

Each test occurs at constant bottle pressure and a constant inlet temperature to the vortex tube. The inlet temperature is manipulated by raising and lowering the main heat exchanger in the liquid nitrogen dewar. The system is run at steady state for 10 minutes before samples are collected.

The Tedlar bags are flushed three times with calibrated air and evacuated by a vacuum pump prior to sample collection. When the bags are being filled the nozzle is first held at an angle for 3-5 seconds within the gas stream while closed to flush any trapped gas. The nozzle is then faced directly into the stream and the bag is filled. This process is followed according to manufacturer recommendation. Bag collection does not change the flow fraction due to extended fill period and bulk discharge in parallel with the bag inlet.

4. Results
The oxygen purity exhausted from both outlets of the vortex tube both with and without an applied magnetic field is shown in Figure 5. Increasing the cold fraction increases the oxygen purity, there is always a higher purity out of the periphery than the core, and applying a magnetic field yields an increase in purity. The maximum oxygen purity achieved, 42.10%, is from the periphery of the vortex tube at a cold fraction of 80% with an applied magnetic field.
Figure 5: Oxygen purity out of both vortex tube outlets, both with and without an applied magnetic field, at cold fractions from 20-80%.

Oxygen purity increases out of both the core and periphery of the vortex tube with increasing cold fraction. The purity from the core remains below that of the inlet stream, and the purity of the periphery is above. The oxygen purity is related to the oxygen yield. Oxygen purity is the percentage of the sample that is oxygen, whereas the oxygen yield is the percentage of oxygen in the sample out of the total in the system. As the oxygen yield increases the oxygen purity from the periphery of the vortex tube decreases and that from the core increases. This is shown in Figure 6.

Figure 6: Oxygen yield versus purity from both vortex tube outlets with and without an applied magnetic field.

The raw data for Figure 5 is shown in Tables 3 and 4. The first standard deviation for the gas chromatograph is 0.42%.
Table 3. Raw data for trials without a magnetic field.

| Cold Fraction (%) | Inlet Temperature (K) | Core Temperature (K) | Periphery Temperature (K) | Core Oxygen Purity (%) | Periphery Oxygen Purity (%) | Pressure Ratio (P_{in}/P_{core}) |
|-------------------|-----------------------|----------------------|---------------------------|------------------------|-----------------------------|---------------------------------|
| 20                | 89.58 ± 0.2545        | 119.00 ± 0.2600      | 84.20 ± 0.2542            | 8.795 ± 0.42           | 24.535 ± 0.42               | 4.5                             |
| 35                | 89.60 ± 0.2545        | 87.00 ± 0.2544       | 87.50 ± 0.2543            | 13.225 ± 0.42          | 24.500 ± 0.42               | 1.8                             |
| 50                | 89.60 ± 0.2545        | 88.50 ± 0.2544       | 88.25 ± 0.2544            | 16.595 ± 0.42          | 25.175 ± 0.42               | 1.8                             |
| 65                | 89.60 ± 0.2545        | 89.00 ± 0.2544       | 88.50 ± 0.2544            | 18.320 ± 0.42          | 25.820 ± 0.42               | 1.7                             |
| 80                | 89.00 ± 0.2545        | 88.50 ± 0.2544       | 88.50 ± 0.2544            | 18.920 ± 0.42          | 27.950 ± 0.42               | 1.6                             |

Note: The input purity is 21.4% oxygen and the remainder nitrogen.

Table 4. Raw data for trials with a magnetic field.

| Cold Fraction (%) | Inlet Temperature (K) | Core Temperature (K) | Periphery Temperature (K) | Core Oxygen Purity (%) | Periphery Oxygen Purity (%) | Pressure Ratio (P_{in}/P_{core}) |
|-------------------|-----------------------|----------------------|---------------------------|------------------------|-----------------------------|---------------------------------|
| 20                | 89.65 ± 0.2545        | 89.70 ± 0.2545       | 160.50 ± 0.2580           | 11.876 ± 0.42          | 21.911 ± 0.42               | 1.7                             |
| 35                | 89.46 ± 0.2545        | 89.45 ± 0.2545       | 123.30 ± 0.2562           | 10.946 ± 0.42          | 27.776 ± 0.42               | 1.6                             |
| 50                | 89.55 ± 0.2545        | 89.95 ± 0.2545       | 100.00 ± 0.2550           | 12.261 ± 0.42          | 30.501 ± 0.42               | 1.5                             |
| 65                | 89.65 ± 0.2545        | 90.00 ± 0.2545       | 89.85 ± 0.2545            | 14.226 ± 0.42          | 33.931 ± 0.42               | 1.5                             |
| 80                | 89.93 ± 0.2545        | 90.85 ± 0.2545       | 89.40 ± 0.2545            | 16.136 ± 0.42          | 42.096 ± 0.42               | 1.5                             |

Note: The input purity is 21.1% oxygen and the remainder nitrogen.

5. Conclusions and Future Work
This experiment investigated whether the paramagnetic behavior of liquid oxygen could significantly aid in separation of oxygen from a condensing air stream in a counter-flow Ranque-Hilsch vortex tube with mounted 1.5 T bar magnets. Increasing the vortex tube cold fraction increases the oxygen purity from the periphery of the vortex tube in both the magnetized (up to 42.09% purity) and non-magnetized cases (up to 27.95% purity). Increasing the oxygen yield of the periphery decreases the oxygen purity from the periphery and increases oxygen purity from the core. These results are with an off-the-shelf vortex tube that is not designed for operation with cryogenic air. Significant improvements in oxygen separation are anticipated if the geometry and test conditions are optimized. Further tests should be completed varying temperature ranges, pressure ratios, cold fractions, and compositions. Additional testing should investigate separation of oxygen from argon due to the difficulty of this separation in distillation columns.

6. References
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