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Oxygen Separation in a Vortex Tube with Applied Magnetic Field

J Raymond, C Bunge, G Henderson, and J Leachman

HYdrogen Properties for Energy Research (HYPER) Laboratory

Washington State University, Pullman, WA 99164-2920 USA

jacob.leachman@wsu.edu

HYdrogen PRoperties for Energy Research Lab

hydrogen.wsu.edu

Introduction: Why is O2 separation important and difficult?

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. The implementation of vortex tubes could potentially result in a cost reduction. Previous works have investigated oxygen separation with non-magnetized vortex tubes or with non-centrifugal magnetization schemes. 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.

Theory: Are centrifugal or paramagnetic forces larger?

The process of inducing vortical flow within a tube with no moving parts was first explored by Georges Ranque and patented in 1933 for cooling (and heating) applications. Nearly two decades later the modern counter-flow vortex tube as seen in Figure 1 was developed by Rudolf Hilsch. With no moving parts or electricity requirements, the device proved to be extremely reliable and inexpensive. 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.

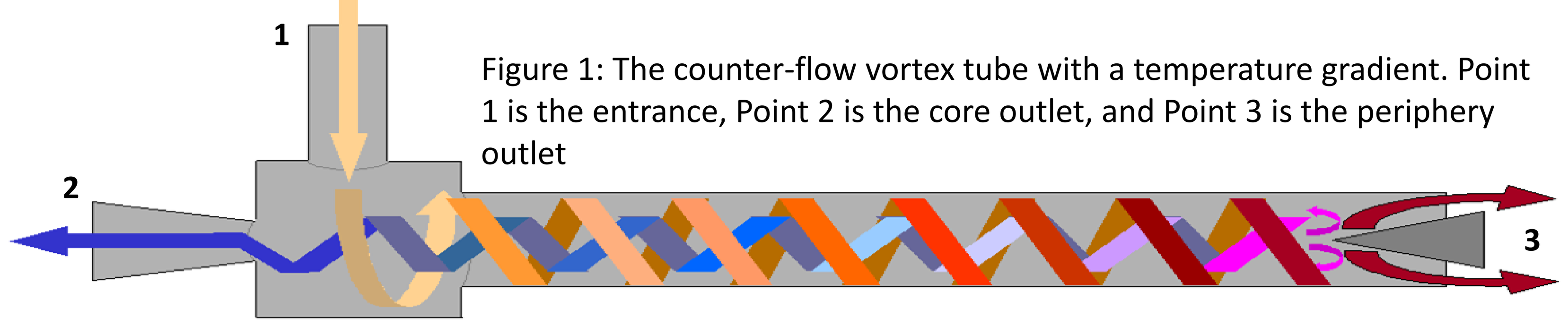
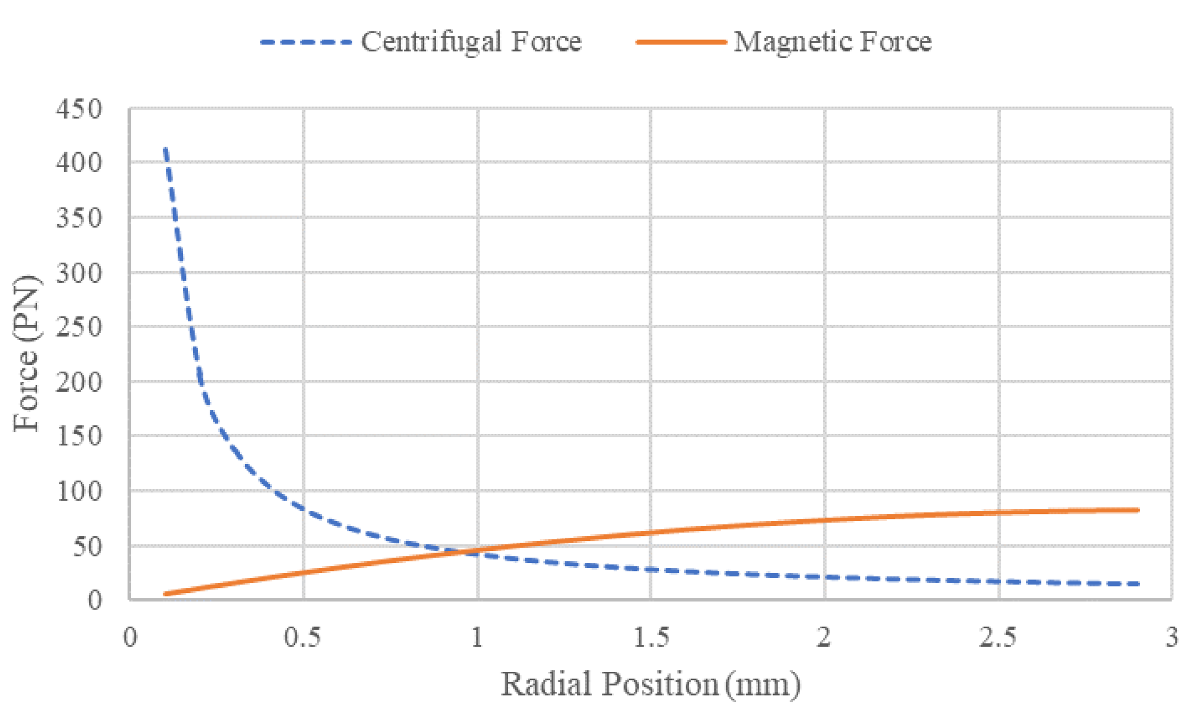


Figure 1: The counter-flow vortex tube with a temperature gradient. Point 1 is the entrance, Point 2 is the core outlet, and Point 3 is the periphery outlet

First order calculations are made to determine whether the paramagnetism of oxygen is significant compared to the dominant centrifugal force within a vortex tube. The centrifugal force is calculated using Equation 1, 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, where F_{Tm} is the total magnetic force acting on the droplet, r_d is the radius of the spherical oxygen droplet, μ_0 is the permeability of free space, χ 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, 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 available rare-earth magnets is significant for vortex tube diameters on the order of half a centimeter.



$$F_c = \frac{mv^2}{r} \quad (1)$$

$$F_{T_m} = \frac{\pi r_d}{2\mu_0^2} * \frac{\chi}{(1+\chi)^2} * B^2 \quad (2)$$

$$F_m = F_{T_m} - F_{T_m} * \left(\frac{r_i - r}{r_i}\right)^2 \quad (3)$$

Figure 2: The magnitude of the magnetic force exceeds that of the centrifugal when the radial position is about 1-mm in a vortex tube with a 3-mm radius. The vortex tube wall is 1.85-mm thick. In this instance the O_2 droplet has a diameter of 0.25 mm and the Mach number is 0.66.

Experimental Design: Building on a Budget

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 at a distance at the end of the periphery outlet as shown in Figure 3.

The experiment schematic is shown in Figure 4. The setup begins with a pressurized bottle of calibrated air with 21.1-21.4% oxygen fraction 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. Three calibrated platinum RTDs, one at each port on the vortex tube, are connected to a Cryocon 24C to monitor the temperature.

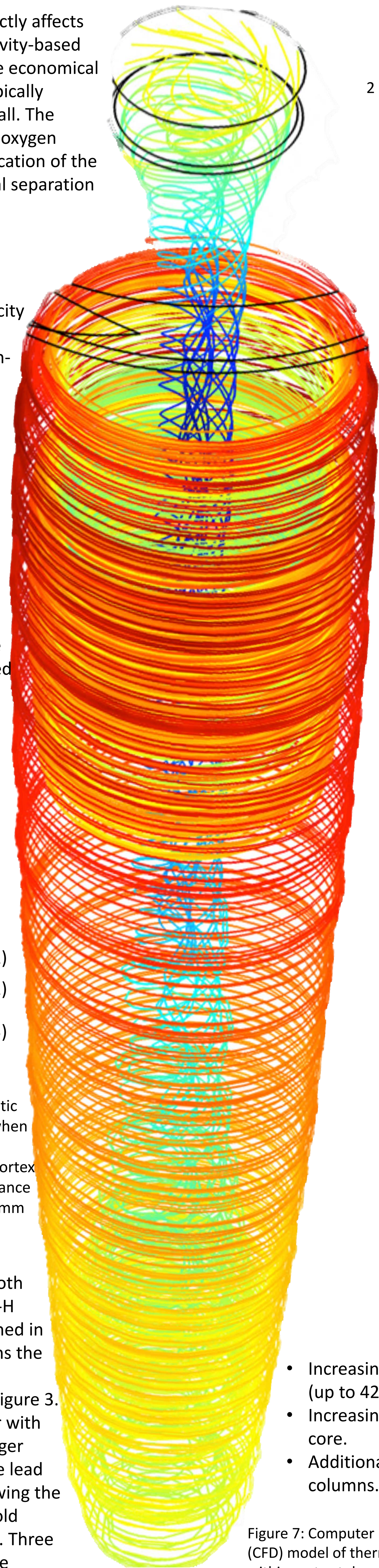


Figure 7: Computer Fluid Dynamic (CFD) model of thermal gradient within vortex tube.

Figure 3: Vortex tube with mounted magnets. Refer to Figure 1 for label explanation.

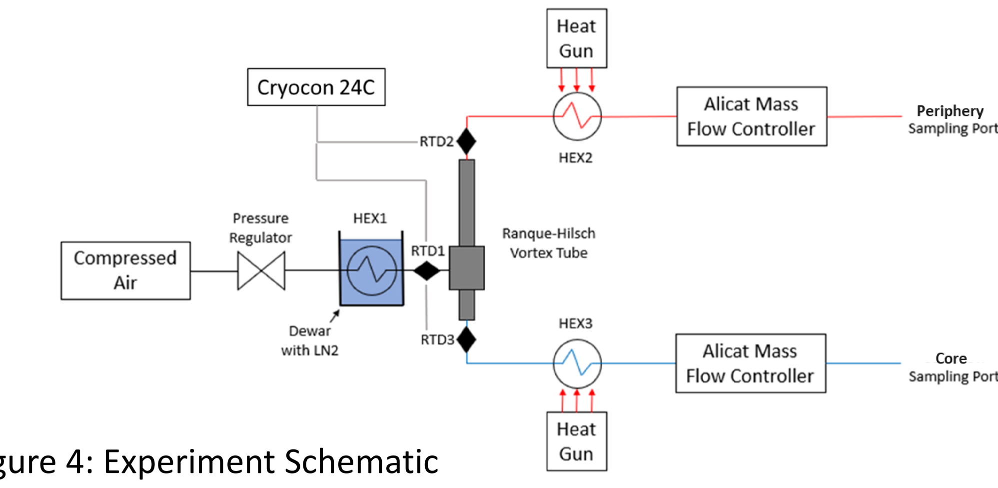


Figure 4: Experiment Schematic

Testing occurs at cold fractions varying 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.

Results: Magnets Double Separation Performance

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.

Oxygen purity increases out of both the core and periphery of the vortex tube with increasing cold fraction. 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.

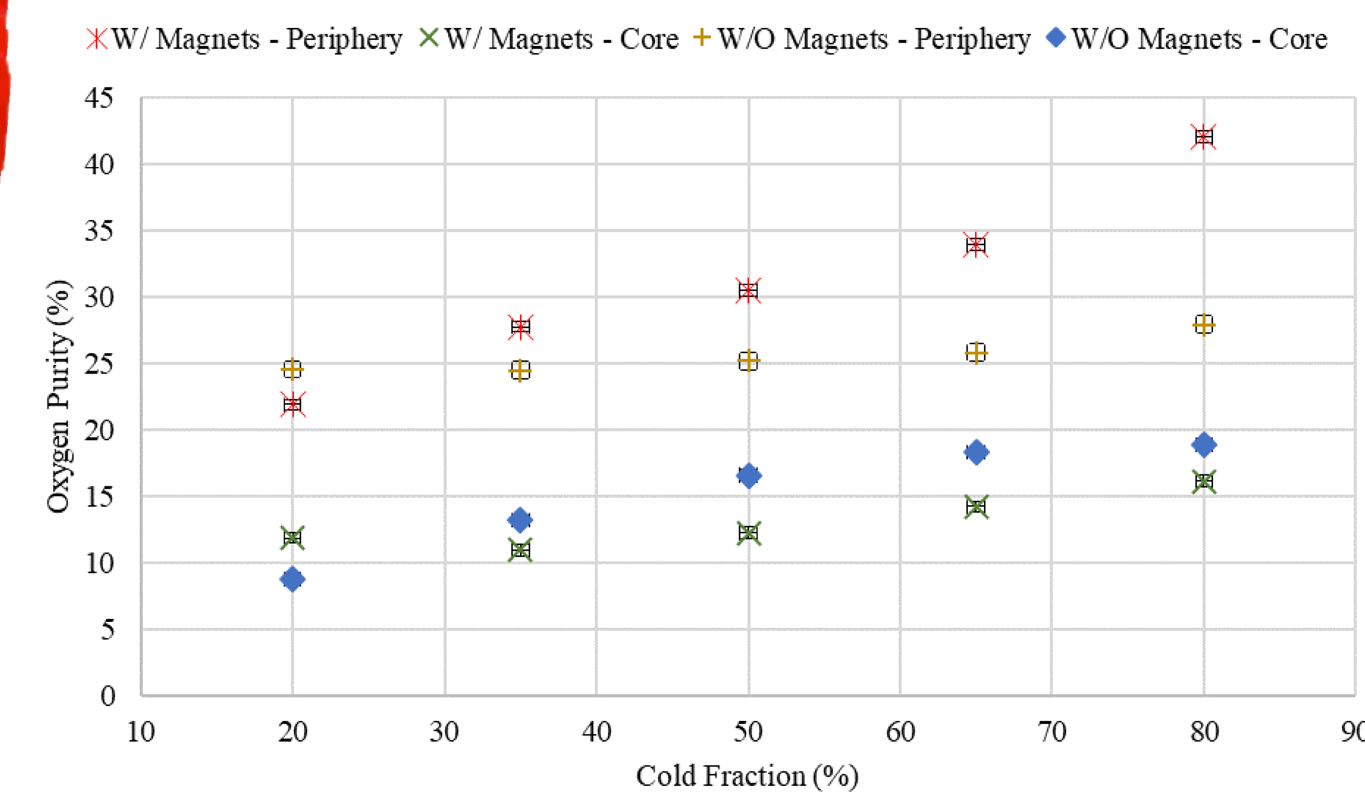


Figure 5: Oxygen purity out of both vortex tube outlets, both with and without an applied magnetic field, at cold fractions from 20-80%.

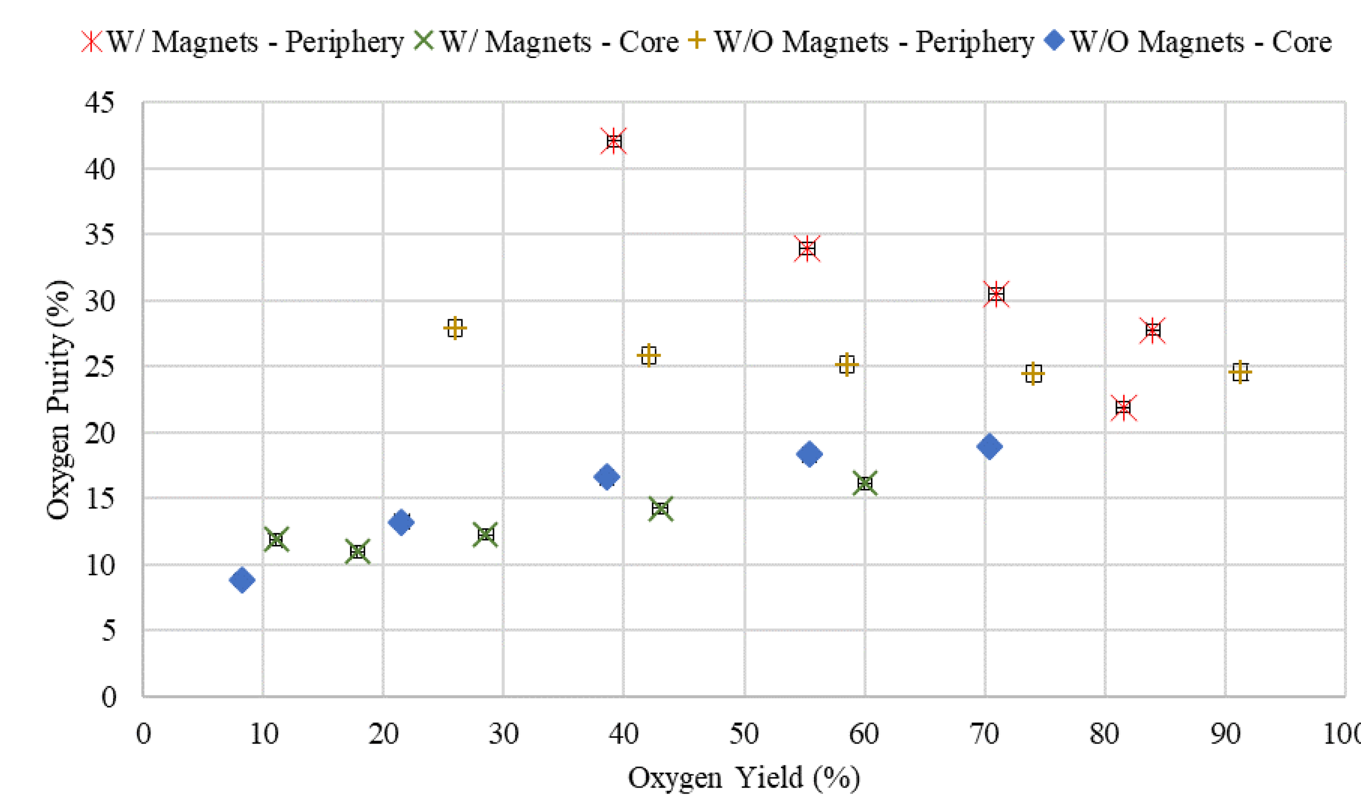


Figure 6: Oxygen yield versus purity from both vortex tube outlets with and without an applied magnetic field.

Highlights, Conclusions, and Recommendations

- 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.
- Additional testing should investigate separation of oxygen from argon due to the difficulty of this separation in distillation columns.

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