EXPERIMENTAL RESULTS OF A VORTEX TUBE AIR SEPARATOR FOR ADVANCED SPACE TRANSPORTATION

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Abstract

Vortex tubes have the potential to be utilized in a compact air separation system that can extract and liquefy oxygen for many purposes, including on-board propellant generation for rocket vehicles. A theoretical and experimental investigation of the operating conditions of a two-phase flow vortex tube is being carried out to determine means to improve its air separation capabilities. Theoretical modeling indicates vortex tube performance may reach 90% oxygen purity at 90% yield. An experimental program has been initiated to provide calibration data for the theoretical modeling and to investigate the multitudes of factors involved with the vortex tube air separation process. Experiments with vortex tubes having taper angles ranging from 0º to 6º have been carried out with mixed-phase air at flow rates up to 3000 SLM. Oxygen purities of 60% at yields of 20% have been demonstrated in preliminary experiments and some of the essential operating characteristics of a two-phase flow vortex tube have been identified.

Introduction

A vortex tube is a device with no moving parts (specifically, a tube or pipe) that will convert an incoming compressed fluid stream (such as air) of homogeneous temperature into two streams of different temperature, one warmer than the inlet and one cooler (see Figure 1). By injecting compressed air at room temperature circumferentially into a tube at high velocity, a vortex tube can produce cold air down to 223 K and hot air up to 400 K. The resulting vortex spins annularly along the tube inner walls as it moves axially down the tube. Part of the air is adiabatically expanded inward to the center. The decrease in pressure during expansion causes a decrease in temperature, which provides a cooler center column of air. The cold air typically is directed out one end (“the cold end”) of the tube, and the warm air at the periphery is exhausted out of the other end (“the warm end”). Temperature and air flow rates are controllable by adjusting valves on either end of the tube. Figure 1 shows a schematic of the flow field within a single-phase vortex tube. The inlet air is injected circumferentially at one end of the tube and part of the air is removed at the opposite end. As the flow moves toward the warm end some of the air expands to the central core and exits at the cold end.
Vortex tubes are used commonly for industrial purposes: to cool machinery during operation (e.g., mold tools, sewing needles, and soldering), to cool workers, to test thermostats, etc. They are popular for their reliability (no moving parts), lack of maintenance, and simple and inexpensive construction (usually made of stainless steel or aluminum).

There have been numerous investigations into the mechanism behind the energy separation observed in the vortex tube. Many different theoretical, computational, and experimental studies have seemingly all yielded different explanations. Lee et al. provide a compilation of previous vortex tube studies in a 2003 AIAA paper.

Explanations and models involving turbulence and compressibility under the influence of a radial pressure gradient in a forced vortex have been proposed for the temperature separation. For example, Cockerill assumed that “the dominant feature of flow in the vortex tube is the swirling flow near the inlet plane,” and that this flow can be described as a forced vortex. Cockerill then develops an empirical model for the temperature separation based on the assumption that the “separation potential” of the vortex tube is proportional to the strength of the forced vortex formed in the inlet region. The concept of heat transfer in a vortex tube via the expansion or contraction of turbulent eddies was proposed by Deissler and Perlmutter, who postulated that “for the case of no net heat transfer, the temperature distribution should be isentropic rather than isothermal.”

In 1982, Kurosaka proposed an alternative mechanism, supported by experiment, for how a vortex tube works. This involved acoustic streaming and the production of a forced vortex, rather than mere static centrifugation. Superimposed upon the counter-flows in the axial direction, flow swirls circumferentially. There is a sudden radial expansion of the vortex core, which is known as either vortex breakdown or bursting. Downstream of the breakdown, there is a recirculating backflow zone. This reversed flow region is followed by unsteady highly turbulent flows having a dominant frequency, which, if and when audible, is heard as the vortex whistle. Also in this region, the vortex core expands radially and its center is located off the vortex tube centerline. This off-centered vortex core starts to precess around the tube periphery, with constant eccentricity. The circumferential movement of the orbiting vortex core, which itself rotates, causes the radial separation of total temperature around the vortex; a moving vortex acts like a compressor-turbine cycle and causes total temperature separation.

**Air Separation**

By far, the majority of past research concerning vortex tubes has been on single-phase systems. However, their ability to separate a common incoming fluid flow into two distinctly different temperature outflows, coupled with the well-established process of distillation, brought them to the attention of researchers interested in the physical separation of air into its constituents for the purposes of using one or both of the main two—nitrogen and oxygen—for other processes. These processes range from generating liquid oxygen from atmospheric air for storage on board in-flight rocket vehicles to emergency services (e.g., on-board replacement of air with nitrogen in aircraft fuel tanks while storing oxygen for aircraft emergencies), military field hospitals, fuel cell installations, or other markets.
needing 50 kg or more of liquid or pure gaseous oxygen per hour. As such, Vortex Tube Air Separators (VTAS) have been studied, modeled, designed, and/or tested in several different countries in recent history.

Just as researchers have debated the mechanism behind the vortex tube’s temperature separation effect, there has been much dispute over mixture, or mass, separation. It has been suggested that liquid centrifugation caused by the rapidly swirling flow is responsible. Assuming this to be true, one may describe the operation of a VTAS as a combination of centrifugation and distillation. In the case of air, the nitrogen concentration is higher in the vapor than in the liquid. In a two-phase vortex tube (Figure 2), vapors swirling in the core region are at high enough temperature to strip out the more volatile component (nitrogen), becoming gradually more concentrated in the vapor, while the less volatile component (oxygen) increases in concentration in the liquid. Centrifugal forces keep the liquid film on the wall, where it can be collected and removed from the tube.

Applying the same theory of adiabatic expansion used in describing the single-phase vortex tube above yields the internal flow field shown schematically in Figure 2. Much like in the single-phase tube, the inlet air stream is injected tangentially so as to induce a vortex motion within the tube. However, in the vortex tube for air separation the inlet air stream is injected with some liquid present (two-phase flow). The liquid fraction in the inlet stream is immediately driven outward to the walls by the centrifugal force induced by the vortex flow and is carried down the tube axially. The vapor present in the inlet flow also travels along the tube adjacent to the liquid film region. As the fluid travels along the tube, a portion of the vapor expands adiabatically toward the counter flowing inner core. During the adiabatic expansion process, the vapor is cooled and droplets of oxygen rich liquid form. These droplets are then flung toward the periphery of the tube by the centrifugal forces. The liquid film collects these droplets as it moves toward the warm end of the tube, while the remaining expanded vapor exits the cold end of the tube. Additional theories for the method of air separation within a vortex tube are also covered by Lee et al.7.

Russian scientists performed much of the early research on two-phase vortex tube air separators. The figures below (Figure 3 and Figure 4) present both a representative sectional view of a Russian vortex tube and experimental results for such a tube configuration9. The primary issue involved with these earlier vortex tube configurations is the relatively low yield (ratio of the amount of oxygen exiting as product to the amount of oxygen entering the system) demonstrated in the experimental testing which produced high product purity, as shown in Figure 4.
In 1988, under a USAF contract, Air Products and Chemicals, Inc. produced a two-phase flow thermodynamic model, which modeled the macroscopic flows in the vortex tube. During this contract, Air Products explored several possible approaches to improve oxygen purity of the liquid product from a conventional VTAS while at the same time increasing the oxygen yields. First, they calibrated the model by fitting available Russian test data. They then proposed and analyzed a number of improvements based on basic fractional distillation thermodynamics and calculated the potential improvements in performance. The “improved” VT features are shown below. Added features are: reflux circulation and external cooling to the “cold end” of the tube to create an oxygen rectifier in the axial flow (Figure 5 and Figure 6), and contoured surface texture to the tube walls to enhance mixing between the fluid layer and the vapor boundary layer (Figure 7).

As shown, these modifications can theoretically improve single stage VT yields and purity from the 60-70% range to the 90+% range. When the NASP program was canceled, however, the results of the Air Products studies saw very limited distribution and the recommended improvements to the VTAS were never tested. The two-phase flow thermodynamic model was also destroyed at the end of the then-classified program, thus no copies exist.

Present Research

Andrews Space was awarded a contract to move from proof-of-principle to proof-of-concept for a VTAS system, with two primary objectives: 1) creation of a two-phase vortex tube thermodynamic model which can be calibrated and validated with experimental results; 2) design, fabrication, and testing of a modular vortex tube experimental unit.

Vortex Tube Modeling

One of the original creators of the Air Products model, Dr. Robert Weimer, was recruited to reconstruct and update the two-phase fluid flow model. Current computing resources and computerized fluid thermodynamic properties models have yielded a superior product that will be used with experimental calibration. The major change from the 1988 model is that exact thermodynamic properties calculated using the National Institute of Standards and Technology REFPROP routines replace simplifying assumptions such as constant heat capacity and constant heat of vaporization. This was not practical for a simple PC-based program in 1988. In addition to providing for more accurate properties,
this change allows many of the equations in the model to be derived in terms of fundamental thermodynamic variables that apply to both single-phase and two-phase flows. Although the model has some theoretical basis, its purpose is to serve as a correlating framework with potential predictive value, rather than as a complete first-principles theory of vortex tubes.

Moving from a single phase model that calculates temperature separation in a vortex tube to a two-phase model that takes into account varying fluid compositions involves the addition of a third radial region, namely that of the liquid film. The underlying principle behind the two-phase model is identical to the single-phase model in that the tube is divided into finite sections and transfer rates between the sections are estimated. Mixing, with condensation due to the radial pressure gradient, occurs between the outer and inner vapor regions and the condensate is thrown outward to the liquid film. Heat transfer between the outer vapor and the liquid film causes partial vaporization of the film. The net effect of the condensation and evaporation is to raise the oxygen content of the liquid film. Initial guesses are made for the composition and enthalpy of each region in each section. The flows in each section are converged separately; new guesses are generated for the boundary conditions between sections, and the process is repeated until convergence is reached. Figure 8 presents a functional diagram of the vortex tube performance model software.
The two-phase model also contains empirical parameters used to match tube separation performance to published Russian data. Important input parameters in the two-phase model include inlet pressure, inlet vapor quality, tube geometric parameters, and waste end exit pressure. The model’s predicted vortex tube performance as a function of inlet air quality is given in Figure 9. The model will be calibrated to match experimental results utilizing the empirical parameters previously mentioned.

Experimental Facility
An experimental facility has been developed at the University of Washington’s Department of Aeronautics and Astronautics to investigate the many different variables associated with the process of separating oxygen from air with a vortex tube. The effects of vortex tube geometry, wall temperature, incoming air physical state, product-to-waste stream flow ratio, and many other variables on the purity versus yield of the oxygen product flow are being investigated. Details of the experimental apparatus and the results from preliminary experiments are discussed in this section. A schematic of the experiment setup is given in Figure 10.

The facility was designed to liquefy compressed air at flow rates up to 4400 SLM at a maximum operating pressure of 1.24 MPa. The air is provided at maximum relative humidity of ~0.6%; low humidity air is essential to minimizing tube blockage problems due to icing during the chilling process. The compressed air flow is routed through 32 m of copper tubing (1.3 cm and 1.6 cm O.D.) which is submerged in a liquid nitrogen (LN2) dewar. The dewar rests on a digital scale that enables the LN2 level to be regulated by controlling the gross dewar weight. The nitrogen boil-off is vented outside via a flexible aluminum duct.

The vortex tube assembly is fabricated from primarily 6061 aluminum alloy in a modular manner that allows various components to be readily exchanged between experiments. A schematic of the assembly with a 6 degree tapered vortex tube is shown in Figure 11. The vortex tube itself (20.3 cm in length) is sandwiched between the injector insert and the product stream collector components. The total length of the internal vortex tube chamber is 28.2 cm from the waste stream exit port to the base of the end wall of the product stream collector. The internal bore of the tapered vortex tube starts at 2.54 cm and expands with a constant taper angle and wall thickness (1.27 cm) to the product stream collector manifold, thus the diameter-to-length ratio is ~11 for this test apparatus. A single 4.8 mm diameter passage injects liquefied/mixed phase air tangentially into the 2.54 cm bore of the injector insert. The nitrogen-rich waste stream exits through a port having a diameter of 1.27 cm adjacent to the injector insert. Restrictor orifices can be placed in the plumbing fittings at both the entrance to the injector passage and the waste stream exit port to adjust their respective area blockage ratios.
Figure 10. Vortex Tube Experiment Setup

Figure 11. Experimental vortex tube assembly

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The product stream collector features an adjustable cone valve that can move approximately 1.5 cm into the conical tube to completely seal the internal flow passage. Moving the cone valve from the completely open position into the tapered tube is one means to vary the oxygen product yield. The liquid film on the inside wall of the vortex tube is directed into an annular manifold through two tangential slots at the end of the tapered section. The liquid-vapor product mixture is collected from a port located at the bottom of the manifold and the liquid temperature in the manifold is measured with a thermocouple installed in the horizontal port.

The oxygen-depleted waste and oxygen-rich product streams are each routed through coils submerged in baths of an ethylene-glycol mixture to warm the flows back up to above 0°C. Circulating pumps are used in the baths to facilitate heat transfer. The flows are then passed through metering orifices (described in next section) prior to being vented. Ball valves at the vent exits are used to adjust the internal pressure of the vortex tube and the product-to-waste stream mass flow ratio.

**Instrumentation**

The incoming air flow rate is measured with a mass flow meter with an uncertainty of +/- 1%. Temperature measurements are made with Type E thermocouples at various locations in the system. The pressure transducers have a 0 – 1.4 MPa range with 0.25% full-scale uncertainty and are isolated from the cold fluid by aluminum or stainless steel tubing. Differential pressure measurements are used with 0.05% uncertainty. Waste and product stream compositions are determined with oxygen sensors with accuracy of +/- 2% and a time response of ~30 seconds to a step input. Product and waste stream flow rates are measured with orifice meters upstream of the oxygen concentration sensors. Temperature, pressure, and flow composition upstream and differential pressure across these orifices are used to calculate mass flows within 10% (higher accuracies are expected with additional calibrations).

Data are collected with a PC-based data acquisition system. Instruments are sampled at 10 Hz and the results averaged for a 1 Hz data output. A 2 kHz low pass filter is applied to all data. Individual thermocouple sensor corrections, based on calibrations using the ice-point of water and LN2 temperature, are applied during the data post-processing procedure, which results in an uncertainty of less than 0.2°C in the low temperature measurements. The quality of the partially liquefied air flow prior to it entering the vortex tube is based on the pressure and temperature measurements at a point 10 cm ahead of the injector orifice. The uncertainty of this quality estimate, based on the worst case temperature and pressure measurement errors, is generally within +/- 15%.

**Experimental Procedure**

Experiments begin at room temperature. Basic single-phase air flow characteristics of the vortex tube are established (i.e., the product and waste streams are warmer and cooler than the injected air, respectively) before nitrogen from the supply dewar is introduced into the LN2 bath. Approximately 35-40 liters of LN2 is required to liquefy the incoming air at flow rates between 1000 and 2000 SLM. The tube is initially flooded with liquid air to facilitate it rapidly reaching thermal equilibrium, which usually takes 5-8 minutes. Once the vortex tube assembly has reached thermal equilibrium, the LN2 bath mass is controlled to maintain inlet air flow conditions. The liquid nitrogen level can readily be kept within +/- 5 mm by hand-adjusting the valve on the LN2 supply dewar. Quasi-steady conditions are maintained until the oxygen content of product and waste streams have stabilized for at least 30 seconds.

Once the vortex tube has reached thermal equilibrium, changes are made to the experiment to investigate their effects on tube performance. For example, the exhaust valve on the product stream (downstream of the warming bath and orifice plate) can be used to control the product-to-waste stream mass flow ratio; if this valve is closed—reducing the ratio—an increase in the oxygen purity of the product stream is observed. Small adjustments to the product stream exhaust valve have negligible effect on the internal pressure of the vortex tube, however, because the product-end collection ports are sized to only accept about 25% of the incoming air flow when no cooling is being applied. A means to adjust the tube operating pressure without changing the incoming flow conditions is to change the waste stream exhaust valve position. Alternatively, a flow-restricting orifice can be placed in the fitting at the tube waste stream exit port to achieve the same ends (however, placing a restrictor immediately at the exit port potentially introduces another variable because it directly interacts with the internal flow structure of the vortex tube due to its immediate proximity). The position of the adjustable cone valve is also varied to determine its effect on product stream purity and yield. Cone valves are designed to close off the tangential ports of the product stream collector at approximately 1.5 cm of movement from their full
open positions. Finally, the effects of inlet air flow and quality and injection air pressure on product stream oxygen purity and yield can be ascertained. Air flow is controlled with a throttling valve on the air inlet stream (upstream of the LN$_2$ bath), quality is controlled with a combination of air flow (using the same throttling valve) and air liquefaction in the LN$_2$ bath, and injection pressure is altered by placing an orifice restrictor in the plumbing fitting at the entrance to the vortex tube injector. It should be mentioned that even though incoming air is regulated for constant pressure, the actual mass flow varies as the conditions at the restrictor orifice change. That is, the mass flow passing through the restrictor orifice increases when a greater fraction of the air is liquid (i.e., lower overall air quality).

**Experimental Results**

The authors have completed only part of the first phase of testing as of this publication. The following paragraphs will describe the results to date. It is anticipated that substantially more data will be collected in the remainder of Phase I and II testing. An update to this paper is planned.

The effects of 0º, 3º, and 6º vortex tube taper angles on product stream oxygen purity and yield have been investigated over a wide range of operating conditions. The orifice restrictors used in these experiments were 3.18 mm and 6.35 mm diameter for the injector insert and the waste stream exit, respectively. Although the tests completed to date have covered a broader range of conditions, the results described below are limited to data for which the air pressure entering the injector was in the 0.9-1.0 MPa range for the mixed-phase flow at flow rates of 1600-2200 SLM.

As described above, regulating the fluid mass in the LN$_2$ bath at a given air flow rate enables inlet conditions to be maintained for several hundred seconds at a time. An example of a period of quasi-steady conditions for a 6º tapered vortex tube is shown in Figure 12. In the test period shown, the air flow rate was approximately 1820 SLM with only 1% variation, and the product and waste streams’ purities were nearly constant. It can be seen that the quality of the mixed-phase inlet air (shown at 75-85%) is very sensitive to small changes in air flow rate.

As explained above, a means to increase oxygen purity is to reduce the product-to-waste stream flow ratio by partially closing the product stream exhaust valve (Figure 13). When this valve is closed, the pressure differential across the product and waste stream’s metering orifice decreases and increases, respectively. An increase in product stream oxygen purity is typically observed within 30 sec of the valve adjustment. The oxygen content of the waste stream also increases because a larger fraction of the incoming air flow is routed in this direction. The waste stream oxygen sensor has a higher sensitivity to composition changes than the sensor used for the product measurements; however, it has a slower time response as evident by the nearly 100 sec needed for it to stabilize after the valve adjustment.

![Figure 12. Typical data from quasi-steady period of experiment operation](image-url)
The purity versus yield of the oxygen product stream data under quasi-steady conditions for each of the vortex tubes are compared in Figure 14. Also shown is the “flash” curve for air at one atmosphere. Flashing is adiabatic expansion that separates the liquid from vapor of a mixed-phase air flow; this type of expansion has limited capacity in terms of product purity and yield, as shown. Obviously, the present project aims to significantly exceed the purity versus yield performance of an adiabatic flashing device. As shown in the figure, all three vortex tubes exceeded the performance of a theoretical flashing device by nearly 15% (in terms of purity), separating air with 55% or greater purity at yields up to 20%. The highest purities (approximately 60%) were achieved with the straight (0° taper) and 3° tubes at yields of 13% and 20%, respectively. Preliminary results indicate that 6° tapered tubes are not as effective at separating oxygen as those with smaller taper angles.

Even though there was not much variation in the peak purities measured during the course of these experiments with the three different vortex tubes, there were significant differences in their operational characteristics. Shown in Figure 15 are product oxygen purity data from each tube under similar inlet conditions, when incoming air flow rate properties were slowly changing. The straight tube was found to be the most sensitive to small changes in input conditions, whereas the purity peaks of the 6° tube were generally much broader and less sensitive than either of the other tubes to small variations in the incoming air properties. Thus, it was much easier to maintain quasi-steady flow conditions with the tapered vortex tubes and determine their responses to various adjustments in the control valves.
Temperature and pressure measurements were made at various points inside the vortex tubes to help determine their operating characteristics under cryogenic conditions. The product oxygen purity and yield data from the 3° tapered tube during a period of quasi-steady operation lasting over four minutes are shown in Figure 16. The corresponding temperature measurements of the incoming air flow, product collector manifold, waste exit stream, and internal wall surface at the midpoint of the vortex tube are also shown. The incoming air temperature was maintained at 97 K and pressure at 360 kPa during this period of testing. The internal pressure of the vortex tube was 145 kPa. The temperature of the flow inside the product collector was 110 K, and that of the flow at the waste stream exit port was 88 K, resulting in a temperature separation of 22 K. The surface of the vortex tube inner wall is usually the coldest part of the system, 83 K in this case. Thus, the fluid at the periphery was likely liquid.

It has been observed during the course of these experiments that the peak purity of the product stream often occurs when the temperature separation is most pronounced. This may support the hypothesis that it advantageous for the peripheral vortex flow at the vapor-liquid interface to be warm enough to preferentially boil off the nitrogen from the liquid film at the wall, although oxygen will also vaporize under these conditions. On the other hand, the temperature of the vortex core flow is well below the point of oxygen liquefaction, thus droplets may reform and be centrifuged back out to the periphery.
Conclusions

A theoretical and experimental investigation of the operating conditions of a two-phase flow vortex tube is being carried out in order to improve its air separation capabilities. An updated computer model of the vortex tube air separation process has been developed which incorporates accurate thermochemical data for cryogenic air and its components. The modeling results indicate that enhancing heat transfer between the liquid air film and the peripheral vapor of the vortex will preferentially enrich the oxygen content of the liquid film. Further improvements were also predicted to occur if the waste stream flow was further chilled prior to its exit from the cold end of the vortex tube in order to condense the remaining oxygen and centrifuge it back out to the tube wall.

A concurrent experimental apparatus has been assembled to validate the theoretical modeling and explore the fundamental operating characteristics of two-phase flow vortex tubes. Experiments have been carried out with partially liquefied air at flow rates up to 3000 SLM in vortex tubes having taper angles ranging from 0° to 6°. Peak oxygen purities of 60% at yields of up to 20% have been demonstrated. The sensitivity of the product stream purity to incoming air flow conditions was found to decrease with increasing taper angle. The oxygen separation process did not begin until the internal wall temperature dropped below that of the injected two-phase air. Oxygen purity peaks were observed to coincide with conditions of maximum temperature separation between the product and waste streams of the vortex tube. These results imply that enhancing the energy separation is an essential element for enriching the oxygen content of the product stream of a vortex tube air separator. While all three vortex tubes have shown the capacity to separate oxygen from air at product purities of approximately 15% greater than that possible in an adiabatic expansion device, the results are lower than expected. The tubes do separate the total temperature of single-phase air, thus the basic elements needed for VT operation are certainly being met. Still, the actual flow field of a two-phase vortex tube is not well understood and is the subject of ongoing investigation. Means to control the temperature separation and tube wall surface temperature are also being explored to gain a better understanding of their roles in the air separation process. Also, factors such as nitrogen reflux, surface roughening, and external heating will be investigated and incorporated in to the analytical models.

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References


