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Abstract

The current study is characterized by two distinct phases in the development of the vortex tube (VT) technology as a primary means for in-flight air separation. The purpose of the first phase was to systematically identify parameters that influence oxygen concentration and recovery and to quantify the extent of that influence. To that end, the project team used a series of planned factorial experiments to identify statistically significant variables (factors) and their interactions. These experiments identified a best range of the operating envelope that includes nozzle diameter, orifice diameter, inlet air pressure, and liquid phase content in the inlet air. The best results observed in this envelope were an oxygen content of approximately 68% and a recovery factor of approximately 38%. The primary objectives of the second phase of the current study were to investigate the application effects of the two different air separation efficiency enhancement methods. One of these methods resulted in a concentration increase of 12% and second resulted in a concentration increase of 5%. Several aspects of these methods application are subject to optimize.

Major Parameters

Co = mass oxygen concentration in the enriched airflow, %
f = enriched airflow/inlet airflow ratio, %
hsep = oxygen recovery factor, %
n = nozzle area
o = orifice diameter
p = air pressure in front of the VT, bar
Y = percentage of the liquid phase in the inlet airflow.

Introduction

Air separation for in-flight oxygen collection is listed among enhancing, cutting-edge technologies in the progam paper of NASA Langley's Systems Analysis Office (Ref. 1). According to the study, "...the problem is in producing a separation device that is efficient enough, small enough, and light weight enough, and that produces high enough concentrations of liquid oxygen to more than pay for its presence in terms of vehicle takeoff gross and dry weight. This is difficult for SSTO's where the conventional mechanical separators do not appear to be viable; however, vortex tube, oxygen enrichment devices...may offer a solution...."

The current paper shows the progress in VT air separation technology evaluation and new experimental results. Enhancement of the air separation with VT technology is the first priority of the *Low Speed Systems for Airbreathing Hypersonic Vehicle* project MSE is managing for NASA Langley Research Center. To qualify for hypersonic flight operation, a separation technology must meet the following criteria:

- 90% product purity;
- 50% oxygen recovery; and
- system specific mass not to exceed 10 sec.

Previous studies showed the possibility to obtain high oxygen concentration with the VT (up to 98% in Ref. 2) and enhanced oxygen recovery (Ref. 3).

For the first time, systematic investigation of the influence of the configuration and working parameters of the VT on separation efficiency has been undertaken. The full replicate 2^4 factorial test plan was developed and implemented. At the initial stage of the research, a maximum concentration of 85% to 90% with a recovery factor of 7% to 10% was attained and kept for a three minute period.
Regression analyses of the test results allowed to define optimum values of the four investigated working parameters, namely n, o, p, and Y. At this optimal combination, oxygen concentration, Co=62%, at oxygen recovery factor, hsep=35%, has been obtained (Ref. 4).

Objectives of the current study included the following:

- verifying and improving previous results without VT configuration changes; and
- applying two different methods of the air separation efficiency increase.

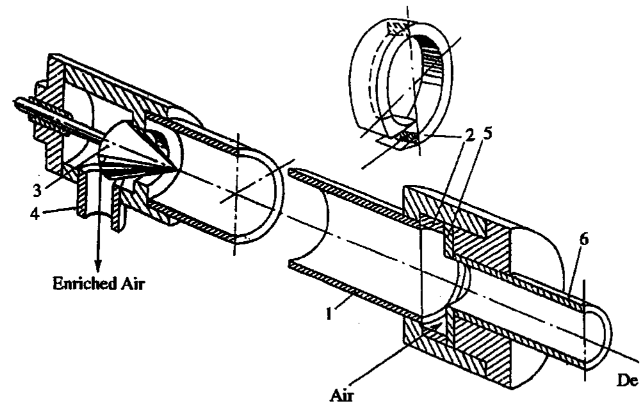

Figure 1. Sections of the VT (1- VT chamber, 2- Nozzle, 3- Exit cone, 4- Diffuser,5- Orifice, and 6- Discharge).

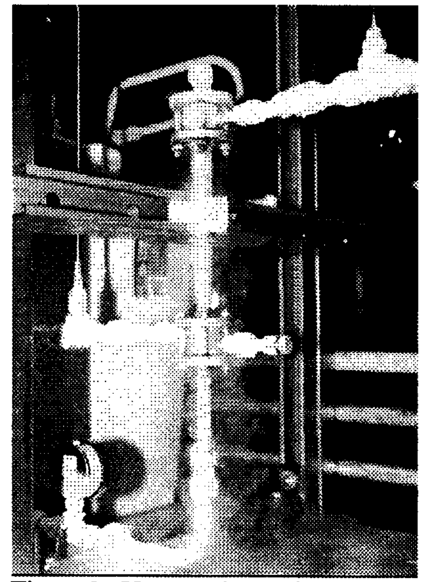

Figure 2. Vortex tube on the test bench.

Air Separation Process

Following is a simple and brief description of VT air separation. Figure 1 indicates the sections of the VT.

Air is cooled to the saturation line, partially condensed, and passed through the VT (1) nozzle (2). The nozzle serves for air injection and vortex generation. In the chambers of the VT, energy separation of the vapor/liquid mixture is accomplished. As a result of the centrifugal force, the liquid is thrown to the wall and flows to the exit cone (3) along the wall. More volatile nitrogen is boiled off from the film near the wall and moves into the backflow area near the VT axis. From the backflow, oxygen is condensed into the liquid film, and the liquid layer enriched with oxygen moves to the diffuser (4). The near-axis vapor flow moves from the cone to the orifice (5). This nitrogen-enriched flow leaves the VT through the outlet (6). The ratio of enriched and depleted airflow is controlled by the variation of the hydraulic resistance of the respective outlet flows controlled with valves. Figure 2 shows the VT mounted on the test bench.

Verification/Optimization Tests

The first task of the current phase was to reassemble the test bench and check its performance. The next task was to duplicate the best operating conditions. After duplicating the previous test results, a search for enhanced concentration/recovery was conducted in the range of the above conditions by varying the inlet air pressure and liquid content (Ref. 4). In several tests, VT performance gradually improved, and the highest oxygen concentration to date (Co=68%) was obtained. The corresponding oxygen recovery factor was hsep=38%. Figure 3 shows fragments of the data recording for test 1.3 where the above parameters were obtained. In this part of test 1.3, VT initially operated at f=1.5 to 3%, and the corresponding concentration and recovery factors were Co=80 to 85% and hsep=6 to 10%, respectively. At approximately 4150s, the enriched air fraction was increased to the target level of f=13%, and the oxygen concentration gradually decreased to Co=67 to 70%. Corresponding air inlet pressure was as low as 2 bar, and the liquid phase content in front of the VT was approximately Y=42% (Figure 3).

It should be noted that maximum VT efficiency was obtained during a four-test series using a higher liquid phase content in front of the VT.

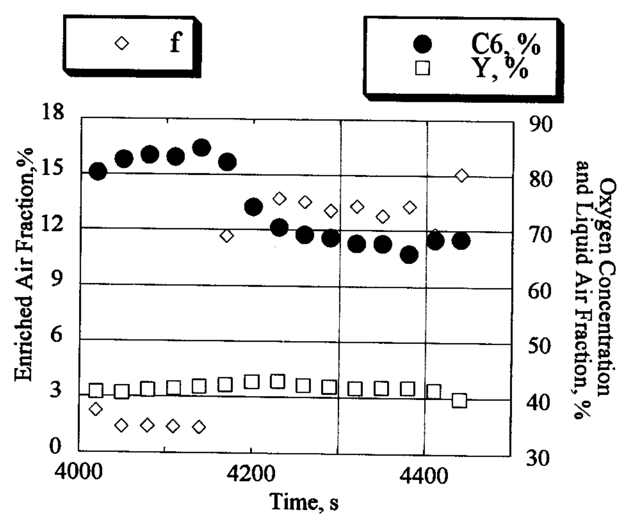

Figure 3. Fragment of test 1.3 data recording.

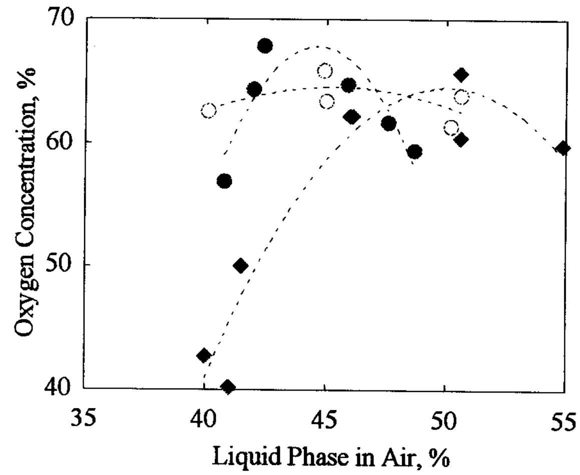

Figure 4. Impact of the liquid phase content on the air separation efficiency (Tests 1.1 to 1.3).

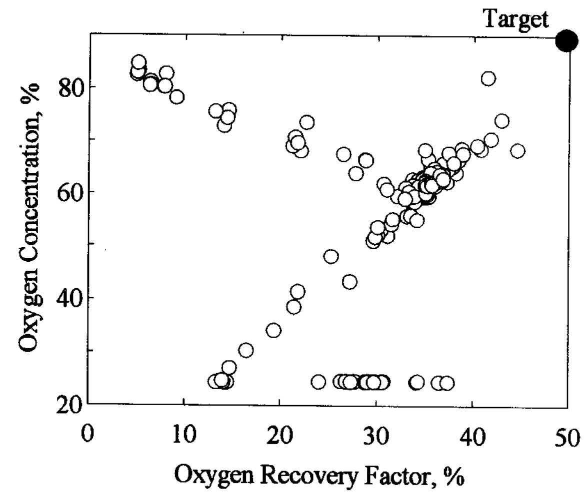

Figure 5. Oxygen concentration versus oxygen recovery factor in test 1.3.

Figure 4 shows oxygen concentration versus liquid phase content for runs 1.1 to 1.3, and according to Figure 4, the optimal range of the liquid fraction is Y=42 to 50%.

Figure 5 shows data from the best optimization test as oxygen concentration versus oxygen recovery factor.

It can be seen that for statistically significant regimes (dense group of points) the recovery approaches 40% and concentration approaches 70%. At a smaller recovery, higher concentration is possible. The oxygen concentration (mass basis) in the enriched air flow at f=13% was taken as the criterion of air separation efficiency. This value corresponds to flow distribution at the target separation efficiency of Co=90% and hsep=50%. In Figure 5, points with f=13% are located on the line connecting target point with Co=23% (oxygen concentation in the air) and hsep=13%.

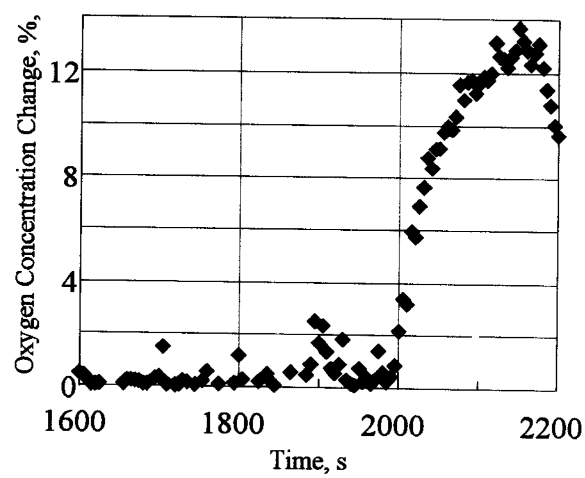

Figure 6. Bypass line impact on oxygen concentration.

Tests with Bypass Operation

Following the optimization tests, a small bypass pipe was installed in the VT assembly to recycle part of the depleted airflow back to the area of the VT inlet. This was an exploration test where neither bypass airflow rate was measured nor the bypass configuration was optimized.

After the bypass was opened, the oxygen concentration gradually increased by 4 to 12%, depending on liquid phase content. In test 2.1, the positive influence of the bypass line was especially remarkable. Figure 6 shows the record of oxygen concentration change after bypass line opening. The test was conducted at an air liquid phase content in front of the VT of Y=44%. In the next test (2.2), the bypass line opening was performed at different Ys. It was observed that Y has influence on oxygen concentration increase with the maximum concentration corresponding to Y=46-48%.

The positive effect from the bypass was obtained in all tests. To take full advantage of this effect, the VT perhaps should be redesigned.

Tests with VT External Heating

An analytical study previously conducted showed that chamber surface of the current VT does not supply enough heat to enhance air separation in the range of the enriched air fraction. This analysis predicted that additional external heating would be beneficial.

Tests 3.1 and 3.2 were devoted to studying external heating effect. Dual-element heat tape was wrapped around the VT chamber. This was also and exploratory tests and no optimization was conducted.

After electric heater initiation, the oxygen concentration immediately started to increase with a standard gas analyzer response time of approximately 20 seconds. The speed of concentration increase was approximately 0.2%/second. This process continued for 20 to 40 seconds, depending on the heating power, followed by a concentration drop resulting from air separation process breakdown. Concentration drop continued until the heater was turned off. After the heater was turned off, gradual concentration recovery to the basic level took place. The clearest case is shown in Figure 7.

It is seen that concentration starts to increase after 20 seconds from heating startup, which is a typical gas analyzer response time. The concentration increases by 5.2% and then starts to drop due to the negative effect of the heat on the distillation process. The time that heating was stopped (70 seconds) is also shown in Figure 7; 20 seconds later the concentration starts to restore to the basic level.

The positive effect of external heating was obtained in the two conducted tests; however, only a small amount of heat and perhaps at a lower temperature level is appropriate for enhancement of the air VT separation process. For example, the VTs bundle shown in Figure 8 could serve as a heat exchange surface of the low-temperature shell-and-tube precooler in an air liquefaction system.
In this case, precooling air will flow between VTs and supply heat to enhance the air separation process.

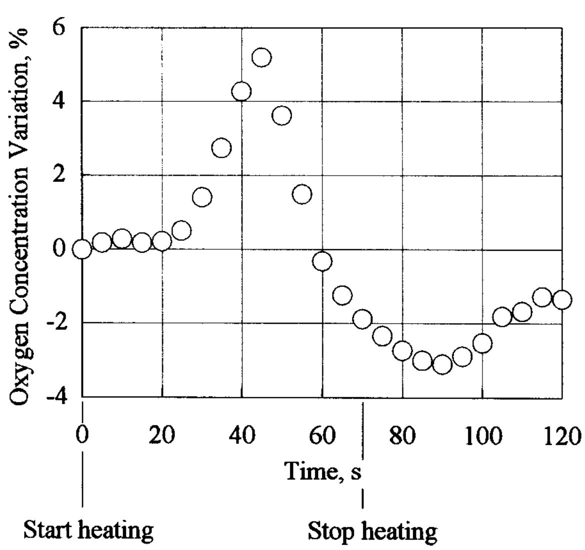

Figure 7. Impact of the external heating on the air separation.

Conclusions

The highest oxygen mass concentration in the enriched air obtained with the VT without additional means of process enhancement was Co=68% at an oxygen recovery factor of hsep=38%. This result was obtained at an enriched airflow fraction (f=13%) that corresponds to an airflow distribution of Co=90% and hsep=50% (the NASA-LaRC initial target for air separation efficiency). The best results were obtained at p=2 bar and Y=42%.

Up to 12% of the concentration increase was demonstrated with a partial recycling of depleted airflow using a bypass line. Five percent of the concentration increase was demonstrated by using external electrical heating of the VT. An appropriate combination of the above effects leads to an air separation efficiency approaching the NASA-LaRC target.

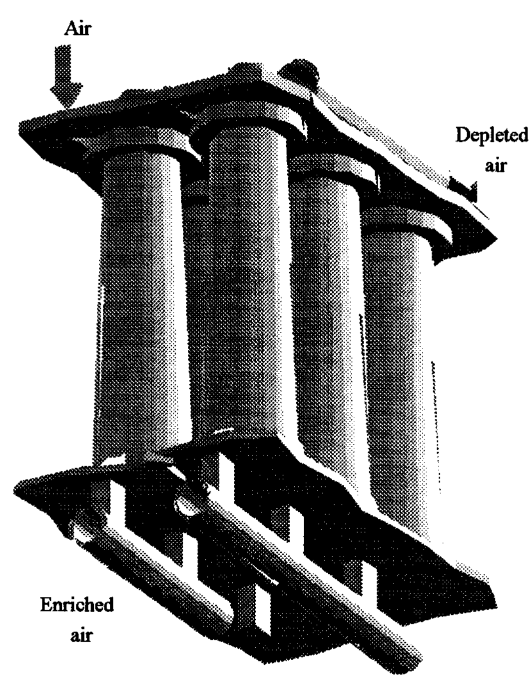

Figure 8. Group of the VTs.

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Acknowledgments

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