



Preliminary investigation of the separation of a binary, two-phase hydrocarbon mixture using a commercially available vortex tube  
by Neil Matthew Spracklen

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in  
Chemical Engineering  
Montana State University  
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**Abstract:**

The vortex tube, a device which is customarily used to effect a temperature separation in an air stream, is being considered for use as a means to separate oxygen from air for potential use in the propulsion systems of hypersonic flight vehicles. For flight vehicle applications, it is desired that the device be capable of producing a liquid stream which is of at least 90 % oxygen purity, and which contains at least 50 % of the oxygen in the feed stream. Although the desired separation has not been achieved to date, the most recent studies have yielded 80-85 % enrichment with recovery in the 30-36 % range.

The fundamental objective of this preliminary investigation was to simulate the desired separation in a commercially available vortex tube, using a system of hydrocarbons as a surrogate for air. It was believed that by using the surrogate mixture in a bench-scale environment, we could come to a better understanding of vortex tube performance without the difficulties and expenses of operating in the cryogenic temperature regime that is required for air systems.

A bench-scale system was constructed, a mixture of 21 % cyclohexane and 79 % n-pentane was selected, and a parametric study was devised to evaluate the effect of feed conditions on vortex tube separation performance.

The desired separation was not achieved using the commercial vortex tube, a unit which was designed for air flow rates much higher than we were using in the bench-scale environment. Modifications were made to the equipment in an effort to compensate for the lower flow rates; however, these modifications did not improve attempts to achieve the desired separation.

All of the data seem to indicate that the best separations achieved in this study were only equivalent to one equilibrium flash stage. Many of the separations did not even match the equilibrium flash case, which suggests that the action of the commercial vortex tube used in this study produced mixing, entrainment, of other processes which serve to reduce the separation when compared to that of an equilibrium flash.

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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## ABSTRACT

The vortex tube, a device which is customarily used to effect a temperature separation in an air stream, is being considered for use as a means to separate oxygen from air for potential use in the propulsion systems of hypersonic flight vehicles. For flight vehicle applications, it is desired that the device be capable of producing a liquid stream which is of at least 90 % oxygen purity, and which contains at least 50 % of the oxygen in the feed stream. Although the desired separation has not been achieved to date, the most recent studies have yielded 80-85 % enrichment with recovery in the 30-36 % range.

The fundamental objective of this preliminary investigation was to simulate the desired separation in a commercially available vortex tube, using a system of hydrocarbons as a surrogate for air. It was believed that by using the surrogate mixture in a bench-scale environment, we could come to a better understanding of vortex tube performance without the difficulties and expenses of operating in the cryogenic temperature regime that is required for air systems.

A bench-scale system was constructed, a mixture of 21 % cyclohexane and 79 % n-pentane was selected, and a parametric study was devised to evaluate the effect of feed conditions on vortex tube separation performance.

The desired separation was not achieved using the commercial vortex tube, a unit which was designed for air flow rates much higher than we were using in the bench-scale environment. Modifications were made to the equipment in an effort to compensate for the lower flow rates; however, these modifications did not improve attempts to achieve the desired separation.

All of the data seem to indicate that the best separations achieved in this study were only equivalent to one equilibrium flash stage. Many of the separations did not even match the equilibrium flash case, which suggests that the action of the commercial vortex tube used in this study produced mixing, entrainment, or other processes which serve to reduce the separation when compared to that of an equilibrium flash.

## CHAPTER 1

### INTRODUCTION

#### Project Framework

Since the early 1960's, there has been considerable interest in developing a system for hypersonic flight vehicles which could eliminate the necessity of carrying large quantities liquid oxygen from takeoff. One such concept employs utilization of an air collection and enrichment system, whereby a two-stage air-breathing vehicle collects air while traveling to orbit, eliminates most of the nitrogen component of the collected air, and selectively stores liquid enriched air which is about 90% oxygen. The ability to acquire en-route the necessary amount of liquid enriched oxygen to be used in the second stage of propulsion (rocket mode) beyond the air-breathing envelope can cut the takeoff weight in half, allowing the vehicle to carry a much greater payload (Maurice 316).

#### Project Overview

Efforts are currently being made to develop a system in a space vehicle which is capable of separating and storing a liquid oxygen enriched product stream from air collected en-route to orbit. Our specific research interests focus on the actual process which will effect the separation.

Phase One of this research project, completed in 1997, included an evaluation of various air separation technologies for use as air collection and enrichment systems (hereafter, ACES) on board space vehicles which utilize air-breathing rocket boosters for propulsion during the first stage of flight. Many air separation technologies were considered, but it was concluded that most conventional air separation technologies would be prohibitively large in volume and weight to be efficiently used in hypersonic flight (Binau 141-42). However, the Phase One study suggested that a system which employs the principle of combined differential condensation and differential vaporization has the potential to carry out the separation.

A device which may employ the combined processes of differential condensation and differential vaporization is the vortex tube, in that the overall process occurring in the vortex tube involves partial condensation and re-vaporization of a partially condensed feed. Although this device shows promise with respect to equipment weight and volume considerations, experiments to date have not achieved the desired separation of 90 % oxygen enrichment and 50 % oxygen recovery. The most recent tests by Balepin yielded 80-85 % oxygen enrichment with recovery in the 30-36 % range (Air Collection Systems 417).

Based on Balepin's findings, Phase Two of this project, currently under way, is an attempt to discover whether the desired separation is attainable using a vortex tube.

### Project Goals

The fundamental objective of our portion of Phase Two was to model the separation of air in a vortex tube, with the aim of achieving a minimum separation of 90% O<sub>2</sub> purity and 50% O<sub>2</sub> recovery. Subsequent chapters of this paper address the three goals outlined to meet this objective:

1. Carry out an experiment on a commercially available vortex tube using a surrogate feed mixture of hydrocarbons which would complement the cryogenic investigations using air being carried out by MSE Technology Applications, Inc. of Butte, MT.
2. Through the use of a surrogate hydrocarbon system operating at reasonable temperatures, come to a better understanding of the apparatus and its potential for separation without the expense of the equipment and control difficulties associated with a system operated at cryogenic conditions.
3. Prepare a report on the findings of our investigation.

## CHAPTER 2

### BACKGROUND

#### Literature Review

##### Context of the Project

A widely agreed upon principle in the literature is that for a viable launch vehicle program to exist, it is an absolute economic necessity to be able to produce a vehicle which allows for its major components and systems to be recovered and reused on a continuous basis. Other economic factors which tend to affect the continued development of launch vehicles include a further reduction in overall vehicle cost and an increased payload capacity (Czysz and Murthy 582).

By and large, it is the propellant (oxidizer and fuel) and the propulsion system (rocket, airbreathing engine, or some combination of the two) which not only dictate the complexity of the control systems, the velocity limits and range of the vehicle, and the demands on materials and structures, but also are responsible for a significant and sometimes prohibitive portion of the total initial mass of the vehicle (Balepin et al. 1). Further, the selection of propulsion system determines whether the vehicle is capable of horizontal take-off and horizontal landing, which influences recoverability, flexibility, and facility costs.

In light of the influence the propellant and propulsion system has on the economics and the performance of a hypersonic space vehicle and its associated flight program, it can be proposed that successful and sustainable hypersonic vehicle design will depend on development and advances in propulsion-propellant technology (Czysz and Murthy 582). Thus, one of the great challenges facing developers lies within the task of creating a system which is optimally suited to meet air collection and separation requirements and, at the same time, minimizes equipment volume and mass.

#### Prior Studies of Air Separation Apparatus

Proposals and studies of potential ACES equipment with bias towards use on a hypersonic flight vehicle have been investigated for nearly four decades. While it is not within the scope of this paper to thoroughly account for all of the previous conclusions and selections made, it is perhaps useful to briefly review some of the more conventional separation technologies which have been considered, along with the conclusions made regarding their prospective use in space flight. Also, an abbreviated account of the conclusions drawn from Phase One of the current project will be presented.

Between 1959 and 1967, considerable effort was made to evaluate potential ACES concepts, largely through United States Air Force funding. In the first few years of this period, many conventional land-based air separation technologies were considered, such as co-current spray contactors, nitrogen freeze-out, centrifugation, molecular sieves, membranes, fractional distillation, vortex tubes, and chemical reaction (Maurice, Leingang, and Carreiro 318). The systems were evaluated with a bias toward their

respective potential of meeting a requirement that the involved equipment mass be very small when compared to the mass of the liquid enriched air (LEA) separated and stored during the collection phase. The conclusion was made in 1961 that the processes of fractional distillation and chemical reaction were the best candidates for meeting this requirement.

The chemical reaction concept considered utilizes the peroxide reaction. Barium oxide or cobalt oxide is used to extract oxygen from air at high temperature and pressure, forming a peroxide. The mixture is then subjected to a lower pressure which induces the peroxide to release oxygen and revert to the metal oxide. On the other hand, the fractional distillation concept employs a vapor phase being bubbled through successive stages of counter-flowing liquid, promoting oxygen enrichment of the liquid and nitrogen enrichment of the vapor. While the chemical reaction air separation concept seemed to be attractive on the basis of equipment weight and product recovery capabilities, it was eventually abandoned due to the mechanical complexities associated with the extremely high temperatures created by the highly exothermic oxygen extraction reaction. Consequently, a majority of the ACES research from that point on has focused on the development of various schemes of fractional distillation.

Cryogenic fractional distillation as a process to separate oxygen from air has been utilized in land-based systems for many years. While a much more detailed description of the process can be found in the literature (McCabe and Smith; Perry; Leingang, Maurice, and Carreiro 344-54), the general framework for fractional distillation for use in ACES involves the utilization of two distillation columns, one operated at high pressure



(near five atmospheres) and one operated at low pressure (atmospheric pressure). The feed mixture is compressed and fed into the bottom column (the high pressure column). The vapor stream from the top of this high pressure column is enriched in nitrogen, and is condensed by exchanging heat with the oxygen enriched liquid stream from the low pressure column in the reboiler-condenser, which is located between the two columns. This exchange further enriches the liquid stream from the low pressure column in oxygen, and as a result, product of high purity liquid oxygen is recovered. The vapor stream from the high pressure column is then returned as feed to both the high and the low pressure columns. High purity nitrogen vapor is recovered from the top of the low pressure column. Hydrogen is used to provide refrigeration in the reflux condenser for the low pressure column.

Although the weight and volume of the land-based system was proven to be prohibitively large for use in hypersonic flight vehicles, investigations in the 1960's revealed modifications to the land-based system which had a significant impact on the weight and volume (Leingang, Maurice, and Carreiro 344-354). The flat distillation trays in the land based unit were replaced with rotary high-g separator cylinders which rotate around their central axis (Nau & Campbell; Bonnet). The centrifugal force created by the rotating cylinder-trays induces the liquid in the system to travel in a crossflow pattern from tray to tray towards the outside of the column. Cylinder rotation also promotes higher vapor velocities, which allows for tighter tray spacing, a significant reduction in equipment size, and operation on a flight vehicle which experiences variable gravitational forces.

As a result of the modifications, both the weight and the volume of the columns in the unit were reduced enough to warrant the construction and testing of a full-scale system for use in hypersonic flight. The tests were quite successful in terms of product purity and recovery, and further, the project was validated in terms of meeting hypersonic flight vehicle weight and volume requirements (Leingang, Maurice, and Carreiro 350). Despite the successful test project, there is nothing available in the literature to suggest the rotary high-g fractional distillation concept has been further explored for use in hypersonic flight applications.

#### Phase One Investigation

Mentioned in the introduction, Phase One of the current research project was completed in 1997. The goal of the Phase One study was to screen available land-based air separation technologies for potential use in hypersonic flight vehicles. Technologies considered during this study included the following: silver, mixed conducting, polymeric, and facilitated transport membranes; reversible chemical reactions with molten salts, solid metallic oxides, and transition metal complexes; solid state adsorption; vapor liquid equilibrium; and magnetic fields.

One fundamental critical criterion used for screening was that any potential technology had to meet weight and volume requirements. Specifically, the mass of the system divided by the inlet air mass flowrate could not exceed 10 lbs/(lbs/s), and the volume of the system divided by the inlet air mass flowrate could not exceed 0.5 ft<sup>3</sup>/(lbs/s). With a given feed rate of 100 pounds per second to the separation system, this

meant the system had to weigh less than 1000 pounds, and occupy a space less than 50 cubic feet.

In his 1997 report on the Phase One study, Binau concluded that most of the traditional land-based air separations considered would exceed the weight and volume limits. However, it was suggested that certain aspects of vapor-liquid equilibrium technologies seemed to hold the most promise in terms of development of an air separation system which would meet the requirements for this application (Binau 141-42).

Rotary distillation, as described in the previous section, was found to be a vapor-liquid equilibrium system with possibilities. Considering that the original test system was constructed of aluminum and stainless steel (Leingang, Maurice, and Carreiro 346), Binau suggested that by utilizing lower density materials, such as carbon-fiber composites, a significant reduction in weight could be realized (114-15). Thus, the rotary distillation design might deserve further consideration.

Other vapor-liquid equilibrium technologies which Binau felt deserved further consideration included those processes which operate under the premises of differential vaporization and differential condensation (*vide infra*). One system which is thought to operate as a differential vapor-liquid equilibrium separation process is the vortex tube (Binau 140).

### Differential Condensation and Differential Vaporization

Like other vapor-liquid equilibrium processes, differential separations exploit the compositional difference between the vapor and liquid phases that a non-azeotropic, multicomponent mixture will possess when it exists in the two-phase regime.

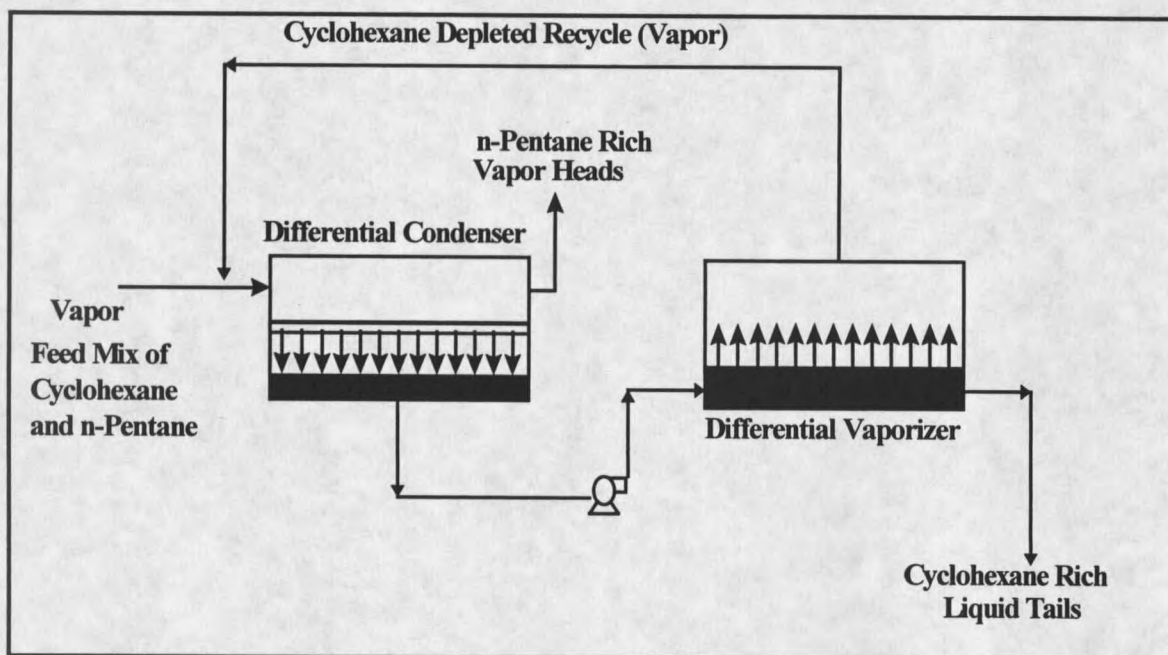
In a differential separation process, small amounts of a multicomponent feed stream are removed and segregated in a fashion which prohibits mixing or mass transfer between the two resulting (product) streams. The two general categories of differential separation processes are differential condensation and differential vaporization.

In differential condensation, the stream consisting of the removed product, or liquid tails, is depleted in the more volatile component. What is left of the original feed stream, or vapor heads, becomes increasingly enriched in the volatile component as it proceeds through the condenser. Differential vaporization operates similarly, except that the vapor heads stream being removed from the feed is enriched in the more volatile component, while the residual liquid tails becomes increasingly depleted in this component.

Viewed another way, differential condensation allows for some enrichment and high recovery of the more volatile component in the vapor heads, while differential vaporization allows for high enrichment of this same component, but at a lower recovery. Thus, the individual differential processes demand a tradeoff between enrichment and recovery.

McCandless, in his investigations of separating oxygen from air, has shown that a combination of the two processes allows for high recovery coupled with very high

degrees of enrichment (Air Enrichment I 20-22). In these investigations, for moderate relative volatilities, both enrichment and recovery were greater than 95 %. Figure 1 shows a simplified schematic of a recycle process which involves differential condensation followed by differential vaporization of the liquid tails stream.



**Figure 1. A combined differential separation process with recycle**

Furthermore, when considering the separation of oxygen from air, both Binau (120-23) and McCandless (25-30) have suggested that, when compared to either ordinary distillation or flash condensation followed by flash vaporization, the combined process of differential condensation followed by differential vaporization with recycle is theoretically more efficient in terms of stages required for separation. Consequently a more compact system can be developed.

The exhaustive literature search in Phase One of the current study resulted in the conclusion that the overall process of differential condensation followed by differential vaporization is favored over any other process to meet the goals of the project for separating oxygen from air (Binau 131-32). However, while differential separation processes are attractive from a theoretical standpoint, development of hardware to carry out a combined differential separation process would be very difficult, due to the requirement that the discrete amounts of product removed from the feed stream must not be allowed to accumulate prior to removal, and sections of the feed stream, which are at different stages of composition, must not be allowed to mix or escape with the removed product stream (Binau 123-24).

As will be discussed in the next section, it is believed that the mechanism for separation in a device known as the vortex tube is a combination of processes which approach that of differential condensation coupled with differential vaporization.

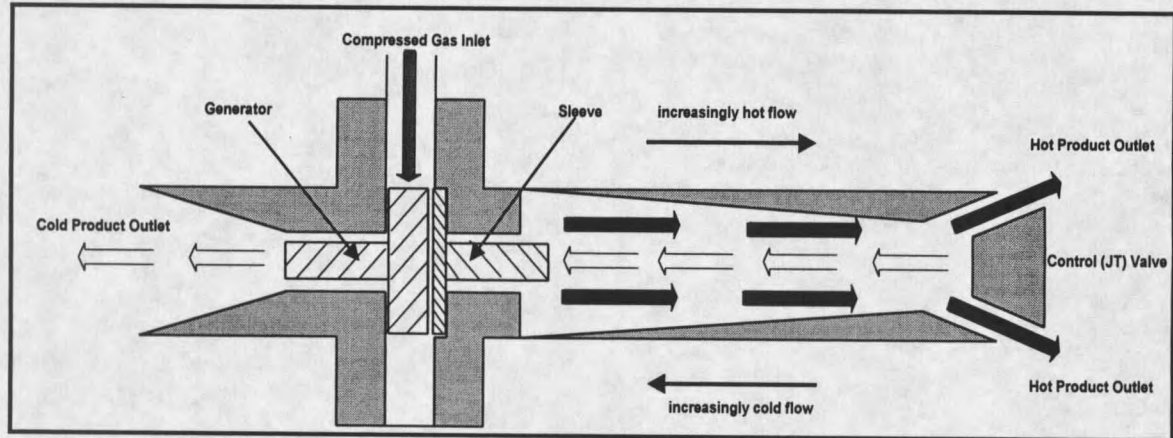
### The Vortex Tube

History. First conceived by Georges Ranque in the early 1930's, the counter-flow vortex tube is a mechanically simple device which separates a high pressure gas stream (typically air) into two product streams, one hotter and one cooler than the feed stream temperature (Ranque 1-6). The simplicity of the device lies in the fact that no mechanically moving parts are required to effect the stream separation. It is reported vortex tubes can produce streams with temperatures ranging from  $-40^{\circ}\text{C}$  to  $121^{\circ}\text{C}$ ,

depending on the fraction of air released from the "hot" end, and subject to energy balances (ITW Vortec® Corp).

While the concept of replacing conventional refrigeration or heating systems with such a simple and compact device may appear attractive initially, it is well known that the vortex tube operations are thermodynamically inefficient (Bruno 988). A ratio of cooling achieved to compression energy required reveals the efficiency of this device to typically range from 10 to 15 % for air systems (Hadjik et al. 77). As a result, applications for the vortex tube have mainly been limited to those circumstances where small size, light weight, or intensely focused spot heating or cooling is required (Young and McCutcheon 522).

Operation and Theories. A cross-sectional schematic of a typical vortex tube configuration is given in Figure 2.

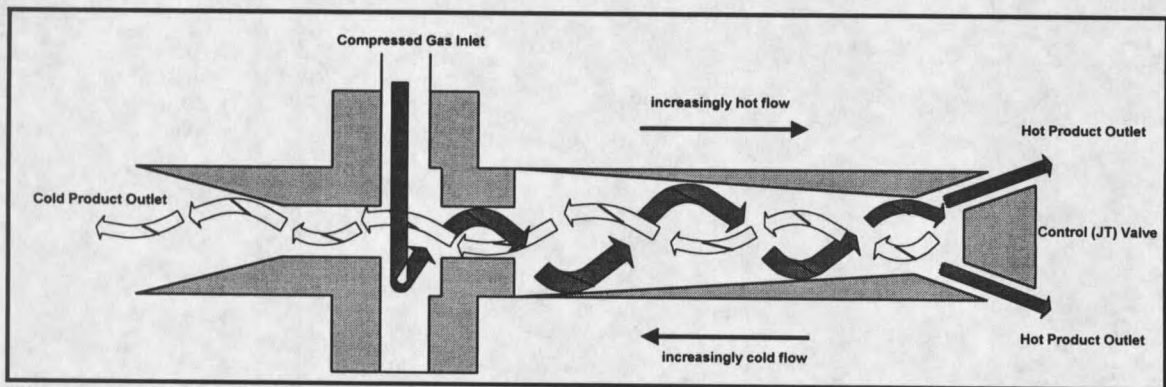


**Figure 2. Schematic diagram of a typical vortex tube.**

In the customary usage of the vortex tube, a source of compressed air is directed to the inlet nozzle, and passed through a vortex generator and sleeve. Once through the generator and sleeve, the gas is fed tangentially into the vortex tube, which is maintained at a low (near atmospheric) pressure. Introduction to the low pressure causes the gas to expand, and consequently, speed up to near sonic velocity (Bruno 987). As a result of the tangential introduction, a vortex is created, and as Craze notes, "the vortex thus formed creates an intense centrifugal field within which gas dynamic transport processes and to a lesser extent Joule-Thompson (JT) cooling establish temperature, pressure, and compositional gradients in the tube both axially and radially" (Craze, lines 24-28). A control valve at one end of the tube allows some of the gas to leave as hot product, while



the rest of the interior gas is redirected into an inner vortex, which flows in a direction linearly opposite to that of the outer vortex, as demonstrated in Figure 3 below. As a point of clarification, the inner vortex is allowed to pass through an orifice in the generator and sleeve on its way to the cold product outlet.



**Figure 3. Flow patterns of the two vortices in the vortex tube.**

While the exact mechanism for energy transfer within the tube is a matter of great controversy (*vide infra*), there is general agreement as to the overall process which occurs. Although the outer and inner vortices are traveling in linearly opposite directions, they rotate in the same angular direction, and with the same angular velocity. Thus, by the principles of conservation of energy and momentum, the inner vortex must lose energy upon its formation. The energy lost as the gas particles move from the outer to the inner core shows up as heat leaving with the gas allowed to escape through the control valve (right-hand side of Figure 3). Consequently, temperature gradients along the length of the tube are established in a fashion which promotes extraction of the hottest gas from

the outer vortex stream at one end, and the coolest gas from the inner vortex core at the opposite end of the tube.

It is not much of an exaggeration to make the statement that, when considering the mechanism of energy transfer in the vortex tube, there are about as many theories as there are investigators, and much of the published work is contradictory.

One theory, proposed by Hilsch (who was instrumental in modifying Ranque's tube to the point of usefulness), attributes the mechanism of energy separation to a change in the swirl velocity profile from a free vortex to a forced vortex, with viscous dissipation producing the radial temperature difference (Hilsch 109-12).

Another often cited proposal to accurately characterize the behavior of the streams in the tube comes from Deissler and Pearlmutter's work in 1960. Employing a turbulent diffusivity, the authors produce an analytical solution to the swirl equation by specifying an axial velocity distribution. Coupling this with the equation of continuity allows for calculation of a radial velocity profile. The crux of this temperature and energy separation mechanism rests on the use of an energy equation which is modified to account for eddy contraction and expansion between the two concentric vortices, where the contraction and expansion is due to a pressure gradient established across the radius of the tube. According to the theory, it is these eddies which are ultimately responsible for transferring the energy between the hot and cold streams (Deissler and Pearlmutter 190).

Yet another popular theory rests on attributing the energy transfer to acoustic streaming, an effect related to the characteristic sound the device makes during operation

more commonly known as the "vortex whistle" (Kurosaka 34-35). A very complex discussion is required to fully explain the nature of this proposed mechanism, and is beyond the scope of this paper. As a simple description, in essence, this theory proposes that there exists a predictable and inseparable relationship between the frequency of the whistle and the degree of temperature separation. Accordingly, understanding the mechanism of whistle generation supposedly means understanding the mechanism of energy transfer.

Overall, it seems the principle reason there is so little agreement on a mechanism of energy transfer is that it is very difficult to physically analyze or analytically model flow which is swirling at an estimated 1,000,000 rpm (ITW Vortec® Corp Corp.) in such a relatively small volume. Most attempts to measure the characteristics of the flow inside the tube have resulted in a disruption of the flow, reducing the performance of the tube, and consequently, causing other investigators to dismiss the work.

As disagreements about the nature of the energy transfer inside the vortex tube have raged for almost 70 years, the thermal separation effected by the vortex tube has, in some circles, been come to be known as "Maxwell's Demon in a tube" (Bruno 987). However, in the next section, it will be shown that the energy separation achieved by the vortex tube, albeit a mysterious phenomenon, violates no thermodynamic laws when viewed as a system.

Thermodynamics. In 1871, Maxwell posed the hypothetical invention of a minuscule "demon" which could sort gas molecules (Zemansky, Abbot, and Van Ness

406-10). This imaginary being functioned as an energy separator, controlling a trap door which partitioned a container filled with gas. As molecules approached the trap door, the demon would allow those with a certain velocity or kinetic energy to pass through it, and, given time, the gas on one side of the door would become hotter and that on the other side cooler. The temperature difference at some point could then be used to operate a perpetual heat engine between the two compartments, in complete violation of the Second Law of Thermodynamics.

While the overall effects of Maxwell's demon and the vortex tube are similar and the lighthearted suggestion of equivalence is sometimes made, the vortex tube has been shown to be far from a perpetual motion device. Further, while Maxwell's demon was envisaged to *separate* gas molecules with a predisposition of heat, the effect of the vortex tube is to *generate* an energy (thermal) gradient in a continuous stream of molecules by inducing a transfer of energy from the center of the tube to the periphery.

To demonstrate the conformity of vortex tube operation to fundamental thermodynamic principles, a discussion will be presented of the First and Second Laws of Thermodynamics as applied to the device.

The First Law of Thermodynamics, as applied to a steady flow process through a control volume, is given by Equation 2.1.

$$\Delta\left[\left(H + \frac{\mu^2}{2g_c} + \frac{zg}{g_c}\right)m\right] = Q - W_s \quad (2.1)$$

In the vortex tube process,  $Q=0$ , as we make the assumption that the device is well insulated and there is little time for heat transfer with the surroundings to take place. As

described in the section above, the device has no moving parts, so  $W_s = 0$ . Neglecting potential and kinetic terms and expanding gives Equation 2.2

$$m_f H_f = m_h H_h + m_c H_c \quad (2.2)$$

where  $m$  represents mass,  $H$  represents enthalpy, and the subscripts  $f$ ,  $c$ , and  $h$  represent the feed, cold, and hot streams, respectively. Equation 2.2 can be written for an ideal gas as:

$$c_p T_f = \mu_c c_p T_c + (1 - \mu_c) c_p T_h \quad (2.3)$$

Here,  $c_p$  is the heat capacity of the gas,  $T$  is the temperature of the stream, and  $\mu$  is the fraction of the inlet mass leaving through the cold exit. Equation 2.3 is commonly used as a convenient means to estimate the cold mass flow fraction from temperature readings when expanding air through the vortex tube.

Equations 2.2 and 2.3 can be used with experimental data to validate that energy is conserved in the vortex tube, and thus the requirements set forth by the First Law of Thermodynamics are satisfied.

With respect to the process under consideration, the Second Law of Thermodynamics states that the total change in entropy as a result of the operation of the vortex tube be equal to or greater than zero. In the form of an inequality, this statement can be quantified as

$$\mu_c (S_c - S_f) + (1 - \mu_c) (S_h - S_f) \geq 0 \quad (2.4)$$

where  $S$  is the molar entropy of a given stream, as represented by the subscripts previously defined.

Analysis of the Second Law does not explicitly permit any given temperature separation to be made with the vortex tube. Rather, application of the Second Law with respect to a particular separation can be used to predict what temperature and energy separations might be *possible*. In other words, while the First Law allows for a wide range of temperature separations to be calculated, the Second Law puts restrictions on this range as to what can be actually achieved with respect to entropy considerations. Therefore, the Second Law can effectively be used to either support a given separation, or reject possible separations that the First Law might suggest possible.

A numerical example of Second Law compliance will not be provided at this point, although explicit examples in the literature can be found to illustrate that the Second Law of Thermodynamics is not violated for given temperature separations using the device (Abbot and Van Ness 227).

## Phase Two Considerations

### Alternative Uses of the Vortex Tube

To this point, discussion of vortex tube operation has, for the most part, focused on the traditional use of the device, which is to effect a separation of air into streams of differing temperature. However, the vortex tube has been investigated for use in many applications which do not necessarily involve the use of a strictly vapor feed stream, and moreover, do not necessarily involve air. Some of the more interesting proposals include removing condensate from natural gas systems (Hajdik et al.), expanding two-phase propane through the tube (Collins and Lovelace), and using the vortex tube as a mass separator to separate isotopes (Schlenker).

Another application of the vortex tube which has been proposed is the separation of oxygen and nitrogen from air, and several authors claim the ability to predict performance in such a system, based on mathematical models which are not explicitly presented in the publications (Suslov, Chizhikov, and Ivanov; Bennett et al.; Yi; Voronin et al.).

Currently, the vortex tube is being considered for the two-phase cryogenic separation of oxygen from air for use in the propulsion systems of hypersonic flight vehicles, as described in the first and second sections of this chapter. Although this device shows promise with respect to equipment weight and volume considerations, experiments to date have not achieved the desired separation of 90 % oxygen enrichment

and 50 % oxygen recovery. The most recent tests yielded 80-85 % oxygen enrichment with recovery in the range of 30-36 % (Balepin Air Collection Systems, 417).

### Two-Phase Flow in the Vortex Tube

What is perceived to occur inside the tube during a component separation with two-phase flow is very similar to that which occurs during temperature separation. Previous research suggests that vortex tube air separations require a high pressure (3.4 to 10.2 atmospheres) feed stream with a liquid content of 20 to 40 % (Voronin et al. Col. 1). As the feed is accelerated through the tangential inlet nozzles and introduced to the relatively low pressure condition in the tube, for the system of air, there is further vaporization. As is the case during single phase flow, a vortex is formed which results in axial and radial temperature gradients. Centrifugal force moves any liquid in the vortex to the periphery, and the temperature gradients promote condensation of the vapor in the inner vortex stream near the inlet nozzle, and vaporization of the liquid in the outer vortex stream near the wall. Eventually, as the liquid condensate migrates down the wall of the tube, it becomes enriched in oxygen (the less volatile component). Likewise, as the vapor in the inner stream is returned towards the inlet nozzle of the tube, it becomes increasingly enriched in the more volatile component, nitrogen. Again, an overall temperature difference is achieved, with the vapor stream (enriched in the low boiler) exiting at a lower temperature than the liquid stream.

It is the complex process of condensation and vaporization (possibly with internal recycle of vapor and liquid) occurring inside the vortex tube which establishes the belief



that this process may possibly be modeled by the theoretical differential separation processes described above. In fact, differential vaporization has been assumed in at least one mathematical model since 1980 (Suslov, Chizhikov, and Ivanov 507).

### Current Project Objectives

The fundamental objective of this component of the Phase Two study was to determine whether a commercially available vortex tube is capable of affecting the desired separation described above. A mixture of hydrocarbons was used as a surrogate for air, in that the mixture did not require operation in the cryogenic temperature regime. Our hope was that through the use of a surrogate hydrocarbon system operating at reasonable temperatures, we could come to a better understanding of the apparatus and its potential for separation without the expense of the equipment and control difficulties associated with a system operated at cryogenic conditions.

## CHAPTER 3

## EXPERIMENTAL INVESTIGATIONS

MaterialsExperimental Overview

When using the vortex tube to separate oxygen from air, the air must first be compressed to high pressures. Then, by throttling the high pressure air to pressures ranging from 50 - 150 psia (3.4 - 10.2 atm), as well as providing additional cooling, a stream can be produced that is less than 30% liquefied (Yi sect. 4). In his patent description, Yi asserts that for a stream which has a pressure of about 100 psia and has been liquefied to a degree somewhat less than 30 %, "generally, the partially liquefied air is in a range of about 170° - 190°R , " or -178.7° to -167.6° C (sect. 4).

Our intent was to carry out a compositional separation investigation on a commercially available vortex tube, and to use a surrogate feed mixture of hydrocarbons which would complement the cryogenic investigations using air which are being carried out by MSE Technology Applications, Inc. of Butte, MT. Our hope was that through the use of a surrogate hydrocarbon system operating at reasonable temperatures, we could come to a better understanding of the apparatus and its potential for separation without the expense of the equipment and control difficulties associated with a system operated at cryogenic conditions.

Surrogate Mixture Selection

For a binary mixture, the phase rule allows for only two intensive variables to be specified arbitrarily in a two phase system. Thus, if temperature and pressure are

variables in the system, the compositions of the equilibrium liquid and vapor phases are necessarily fixed. On the other hand, holding one of the intensive variables fixed allows for calculation of the change in composition as a function of the other variable. Viewing the change in composition of both phases simultaneously as a function of either temperature or pressure (with the other variable fixed) is accomplished through the use of a vapor-liquid equilibrium. Commonly referred to as the relative volatility of the system, this ratio is sometimes used as a measure of the relative ease of separating two components in a binary mixture by distillation. Generally speaking, the higher the relative volatility of a system, the easier it is to separate the components. Also known as the stage separation factor in applications other than distillation, the relationship for constant relative volatility ( $\alpha^*$ ) for a binary system is given in Equation 3.1.

$$\alpha_{ij}^* = \frac{y_i(1-x_i)}{x_i(1-y_i)} \quad (3.1)$$

The mean relative volatility of a system can be calculated by averaging the individual values of the relative volatility over the compositional range of interest.

Numerous substances were initially considered and screened for potential use, including Noble Gases, Halogens, and hydrocarbons. Halogen mixtures, as well as Noble Gas mixtures, proved not only economically prohibitive to obtain, but also required operation of the system under cryogenic conditions. Therefore, efforts were focused on selecting a binary mixture of hydrocarbons.

In selecting a suitable surrogate hydrocarbon system, we made the assumption that separations of systems with a similar relative volatility behave in a similar manner. Table

1 shows the average relative volatility of the oxygen/nitrogen system, as well as several hydrocarbon systems which were screened for potential use. The average relative volatility was calculated at 0.8421 atmospheres (atm), an estimation of the ambient pressure in Bozeman, MT on a given day.

SYSTEM	MEAN RELATIVE VOLATILITY (0.8421 atm)
Oxygen / Nitrogen	4.01
I-Butane / Propane	3.45
N-Pentane / N-Butane	3.75
Cyclohexane / N-Pentane	4.25

**Table 1. Relative volatility of the oxygen/nitrogen system, as well as several hydrocarbon systems screened for potential use.**

The mixture of n-pentane and cyclohexane was chosen for use, as it has a relative volatility quite close to air at atmospheric pressure, and it also exists as a liquid at room temperature and atmospheric pressure. In using a system which exists as a liquid at room temperature, we could increase the pressure and temperature to achieve the desired conditions at the inlet to the vortex tube, rather than throttling down and cooling an already high-pressure system.

Figure 4 is a plot of equilibrium data for a binary system of 21 mole % cyclohexane and 79 mole % n-pentane. The data for this plot was generated by the software package ChemCAD<sup>®</sup> III, where the Soave-Redlich-Kwong (SRK) equation of state was used for determining thermodynamic properties. The SRK model was chosen by the "expert" system in ChemCAD<sup>®</sup> III as being the most appropriate for the system over the pressure

and temperature range of interest. In essence, this is a plot of the relative volatility as a function of pressure. The figure reveals that there is a substantial difference in the composition between the vapor and the liquid phases as pressure is decreased; in other words, for this system the relative volatility increases as pressure decreases. Thus, separation should be easier at lower pressures. Also indicated on Figure 4 is the mean value of the relative volatility for a given pressure.

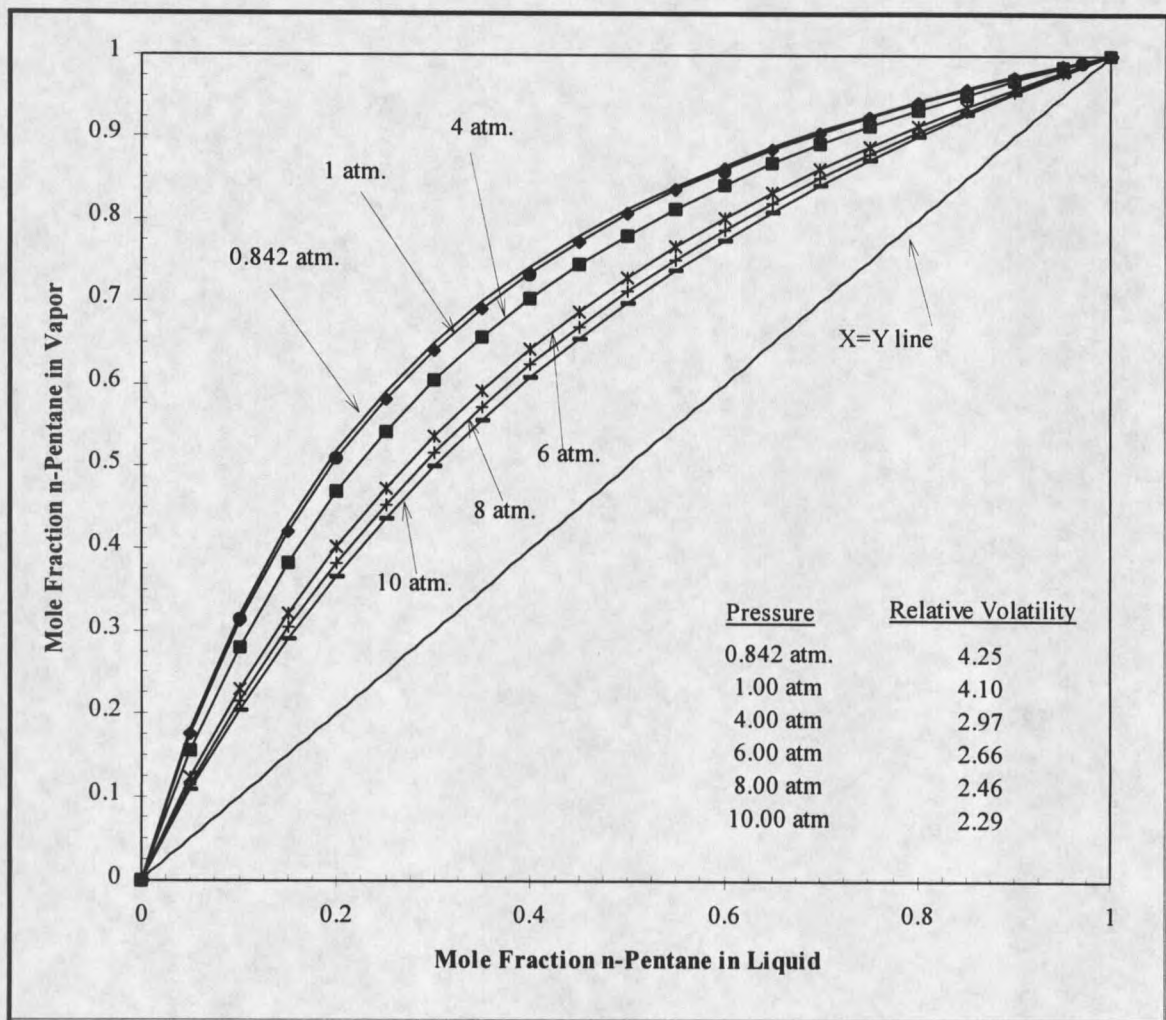


Figure 4. Phase separation of n-pentane in the 21 % cyclohexane / 79 % n-pentane mixture as a function of pressure. Also indicated is the mean relative volatility of the system as a function of pressure.

### Commercial Vortex Tube Selection and Modifications

For bench scale systems, 10 cc/min high pressure pumps are fairly standard. Given that greater pumping capacity necessitates larger equipment and significantly more feed-stock, it was our feeling that this flow rate was a practical maximum for our investigation.

This flow rate of 10 cc/min (or approximately 0.07 standard cubic feet per minute assuming an 80 % vapor feed) for our bench-scale system was a significantly smaller volume than most of the commercial vortex tubes typically handle. The smallest vortex tube we could find was distributed by EXAIR® Corporation. This unit (model number 3208) is 19 mm in length, and designed to be used for air flows ranging from two to eight standard cubic feet per minute (hereafter, scfm). An exploded view of the EXAIR® vortex tube and its components is given below in Figure 5.

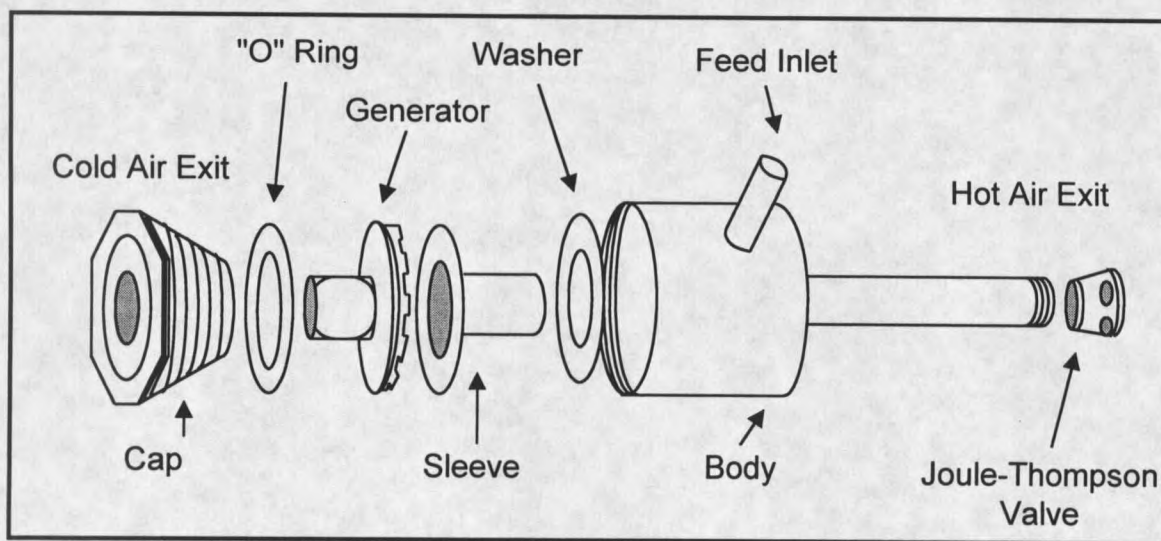


Figure 5. Exploded view of the EXAIR® vortex tube and its associated parts.

We replaced EXAIR's Joule-Thompson valve at the hot (liquid) outlet of the vortex tube with an externally-operated hand valve. This valve allowed us to control the fraction of the feed leaving through the liquid exit. Before placing the vortex tube into operation in our system, we tested the performance of our replacement valve using a compressed air system, and achieved similar temperature and flow rate control as that achieved with the factory Joule-Thompson valve.

As mentioned above, the commercial vortex tube was designed for air flow rates ranging from two to eight scfm. The generator and sleeve depicted in Figure 5 are sized for a particular air flow rate and application; accordingly, several versions of each accompany the tube. For the application of maximum cold flow, there were three GR-series generators provided, one each for the flow rates of two, four, and eight scfm. Likewise, there were three GC-series generators provided for maximum cold temperature of the air. The differences among the generators lies in the sizing, and in general, the GR-series had larger characteristic dimensions (as discussed below) for a given flow rate. With respect to the factory sleeves, one each was provided for the respective flow rates mentioned above.

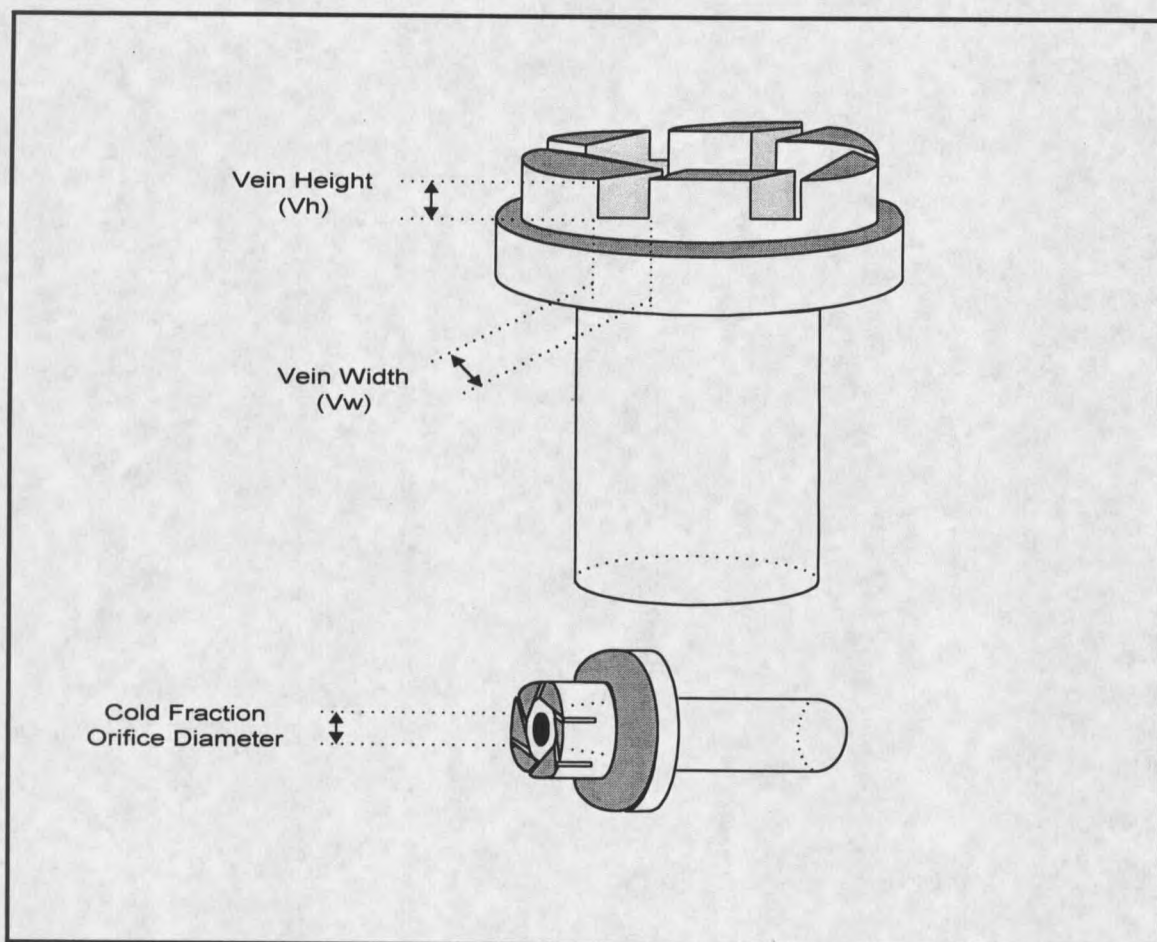
Since our application involved a two-phase mixture of hydrocarbons rather than a single phase flow of air, one of the great uncertainties of this project from the beginning concerned modifications necessary to accommodate the presence of liquid. Indeed, it was unknown how the generator and sleeve would respond to the liquid in the feed in terms of vortex generation. This was compounded by the fact that we were presenting a feed

which is orders of magnitude lower in volume than that which these components were designed to handle.

“Scaling-up” the system to match the minimum flow rate the vortex tube was designed for (two scfm) meant increasing the capacity of our pump by a factor of about thirty. Purchasing a pump which would deliver that amount of flow (as well as the additional costs of increased feedstock, larger volume feed storage vessels, and a larger heat exchanging system) was considered to be both economically unfeasible and beyond the scope of a bench-scale experiment.

Rather, the decision was made to construct a generator and sleeve which might be more congruent with our flow rate of 0.07 scfm. To size these components, we measured dimensions of the components which seemed to be characteristic to a particular flow rate. For the generator, these characteristic dimensions were the feed inlet area and the cold fraction orifice diameter, as depicted in Figure 6.





**Figure 6. Characteristic dimensions of the vortex generator.**

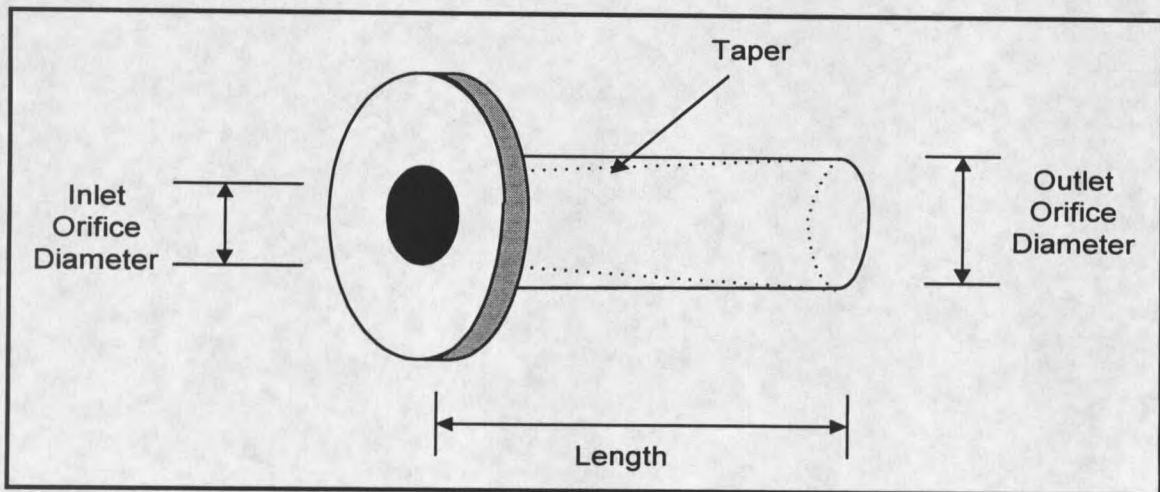
The feed inlet area was determined by calculating the total cross-sectional area of a vein, and multiplying it by the total number of veins (six). An evaluation of the characteristic dimensions of the factory generators for the flow rates our vortex tube was designed for, as well as the dimensions of generators designed for flow rates of 10 to 150 scfm in the larger vortex tubes, revealed a linear relationship between flow rate and feed inlet area. Thus, a linear regression was performed to find the dimensions required for our flow rate of 0.07 scfm.

The sizes of the characteristic dimensions for the GC-Series factory generators (the smaller of the two series mentioned above) and the modified generator are presented below in Table 2.

	FACTORY GENERATOR			MODIFIED GENERATOR		
Flow Rate (SCFM)	Orifice Diameter (inches)	Vein Height (inches)	Vein Width (inches)	Orifice Diameter (inches)	Vein Height (inches)	Vein Width (inches)
0.07	-----	-----	-----	0.047	0.002	0.030
2.0	0.062	0.013	0.030	-----	-----	-----
4.0	0.072	0.016	0.030	-----	-----	-----
8.0	0.092	0.039	0.030	-----	-----	-----

**Table 2. Measurements of the characteristic dimensions of the factory and modified generators.**

In a similar manner, we determined the dimensions of the sleeve which seemed to be characteristic for a given flow rate. These dimensions are depicted in Figure 7, below.



**Figure 7. Characteristic dimensions of the vortex tube sleeve.**

Although we were able to use a linear regression to find the dimensions necessary for our flow rate of 0.07 scfm, we decided to further modify this piece of equipment: rather than simply reduce the inlet and outlet orifices in proportion, we lengthened the entire structure so that it would span the distance between the inlet for the vortex tube and the hot side (liquid) outlet. This modification made the component an effective combination sleeve/insert which narrowed the overall diameter of the vortex tube.

The optimum taper between the outlet and inlet orifices suggested in the literature is 2 to 2.5 degrees, based on a relative length (which is the length of the tube divided by the inlet orifice diameter) of 20 to 22 (Suslov, Chizhikov, and Ivanov 510). However, the calculated inlet orifice based on the length of our vortex tube, the outlet orifice diameter, and 2 to 2.5 degrees of taper would be nearly 1.5 orders of magnitude smaller in diameter than the smallest hole our machinist could drill. Consequently, we decided to use an inlet orifice diameter based on the linear regression described above, along with an outlet orifice diameter based on the vortex tube hot side outlet diameter. Given a length of 1.654 inches, this produces roughly a 0.5 degree taper inside the sleeve/insert we created. Although this is much less than the optimum suggested in the literature, it was our hope that this modified sleeve would effect some measure of improvement in the separation over that which could be achieved using the factory sleeves provided with the vortex tube.

The sizes of the characteristic dimensions of the sleeves provided with the vortex tube, as well as those we created, are presented below in Table 3.

Flow Rate (SCFM)	FACTORY SLEEVE			MODIFIED SLEEVE		
	Inlet Diameter (inches)	Outlet Diameter (inches)	Length (inches)	Inlet Diameter (inches)	Outlet Diameter (inches)	Length (inches)
0.07	-----	-----	-----	0.150	0.179	1.654
2.0	0.1675	0.186	0.674	-----	-----	-----
4.0	0.180	0.205	0.676	-----	-----	-----
8.0	0.205	0.205	0.678	-----	-----	-----

**Table 3. Measurements of the characteristic dimensions of the factory and modified sleeves.**

## Experimental and Analytical Equipment

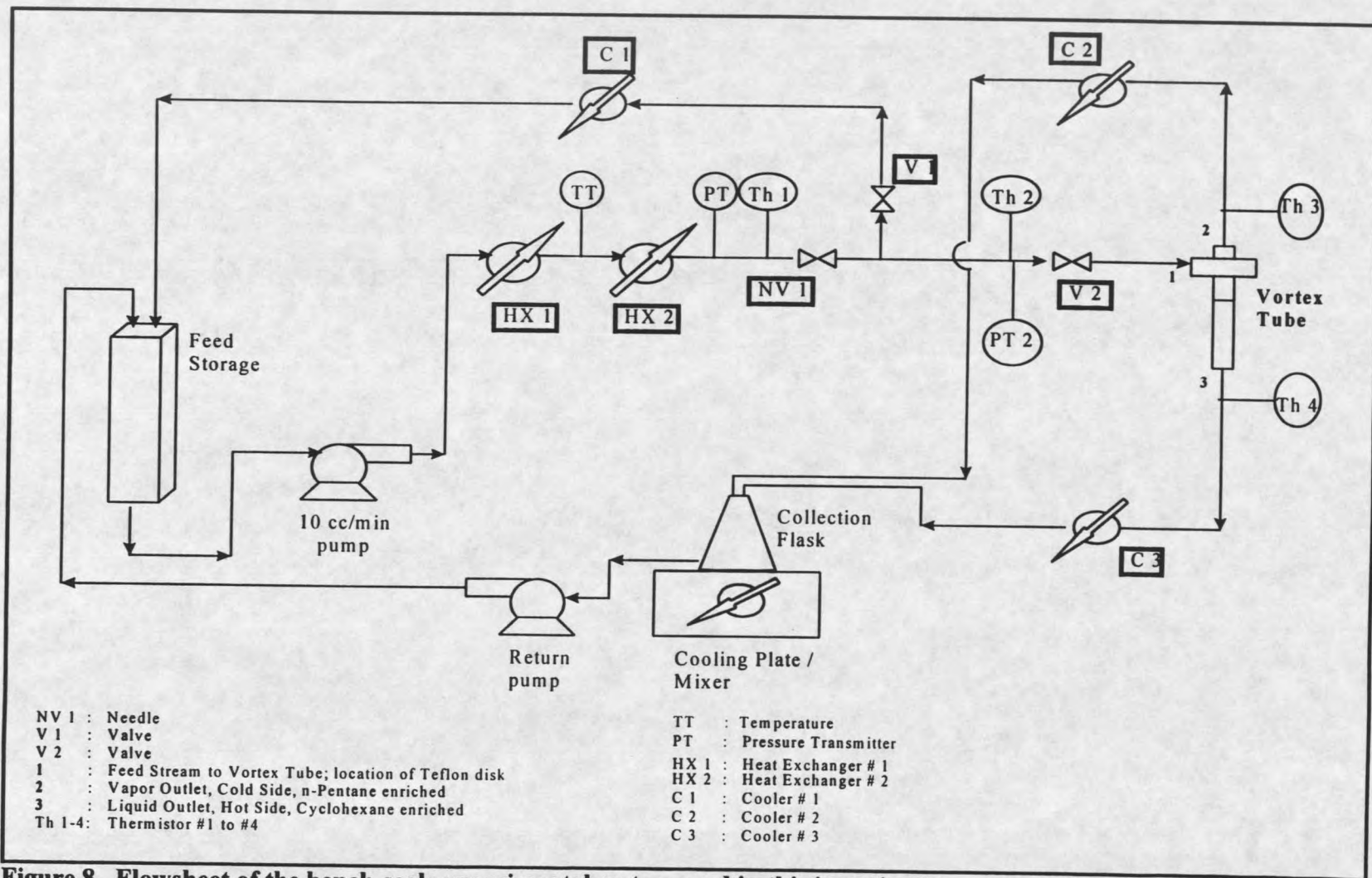
### System Description

General Description. In order to evaluate the potential of achieving the desired separation using a commercially available vortex tube, a bench-scale system was constructed. A general description of the system follows.

The liquid feed mixture is pumped through a recycle loop (without passing through the vortex tube) to allow the system to come to a sort of steady-state operation, where the heat exchangers are operating steadily at the prescribed temperature and pressure. Once the heat exchanging system is running smoothly at the desired conditions, we direct the flow through the vortex tube. The product from each end of the tube is run through a cooler and delivered to a main collection flask, where it is further cooled, mixed, and returned to the feed storage tank. The temperatures of the product streams exiting the tube are monitored by use of both thermocouples and thermistors. Once the system appears to be operating at steady state, for a sampling event, the product streams entering the collection flask are manually directed towards sample collection vials. After the sampling event, the streams are then redirected to the main collection flask for return to the feed tank.

The Detailed System. The following is a more descriptive record of the experimental apparatus we are utilizing to achieve the prescribed separation and recovery. The reader is directed to refer to the accompanying flow sheet, Figure 8.





**Figure 8. Flowsheet of the bench-scale experimental system used in this investigation.**

Approximately 400 cubic centimeters of the 79% n-pentane / 21% cyclohexane mixture is placed in a 500 cubic centimeter storage flask which is maintained at atmospheric pressure and room temperature, but is semi-sealed to minimize vapor release and compositional changes. The mixture is pumped out of the storage flask using a Shimadzu LC-10AD double plunger reciprocating pump with a maximum pumping capacity of 10 cc/min. A needle valve (indicated as "NV 1" on the figure) downstream of the pump is used to control the flowrate to the rest of the system, and allows for the buildup of pressure within the system. The pump delivers the mixture to the first of two heat exchangers (HX 1), where the fluid is heated to the bubble point at the desired pressure. The temperature of the mixture inside this heat exchanger is monitored and controlled using a system of a chromel-alumel thermocouple (TT), a solid state relay, a variable autotransformer, and an Omega CN 380 temperature controller. Next, the mixture enters a second heat exchanger (HX 2) where the temperature of the fluid is increased to the calculated value which will produce the desired feed quality. The exit temperature from HX 2 is monitored and controlled using a duplicate of the system described above, as well as a thermistor (Th 1). The pressure at this point is measured using an Omega PX-215 pressure transducer (PT).

Exiting the heat exchangers, the mixture passes through a manually controlled needle valve (NV 1), which is adjusted to allow pressure build-up upstream to the desired pressure condition. After passing through NV 1, the stream is initially directed to recycle back to the feed tank by opening the hand valve on that stream (V1) and closing the hand valve (V 2) of the stream leading to the vortex tube (1). The recycle stream is run through

a cooler (*C 1*) which brings the mixture back down to below room temperature before it is dumped back into the feed storage flask. Recycle to the feed storage flask is run until the system is operating at steady state at the desired temperature and pressure at the outlet of the second heat exchanger (*HX 2*).

Once steady state is achieved, the recycle stream hand valve (*V 1*) is closed, the hand valve (*V 2*) of the stream leading to the vortex tube (**1**) is opened, and the mixture is directed towards the vortex tube (*VT*) where the separation takes place. Prior to entering the vortex tube, the feed must pass through an orifice in a small Teflon<sup>®</sup> disk we placed immediately upstream of the vortex generator inside the vortex tube. The purpose of this disk is two-fold: the pressure of the stream is increased ahead of it (otherwise the mixture flashes to 1 atm after *NV 1*), and it also increases the velocity of the stream prior to the vortex generator (downstream from the disk). The disk described above maintains a pressure of 2 to 4 atmospheres in the region between it and *NV 1*. Next, we have introduced additional temperature and pressure sensors in the area between *NV 1* and the *VT* in order to have a better grasp on the conditions of the feed entering the *VT*. In Figure 8, the thermistor in this region is labeled as *Th 2*, and the pressure gauge is labeled as *PT 2*.

After passing through the orifice, the feed stream enters the vertically-mounted vortex tube purchased from EXAIR<sup>®</sup> Corporation, as discussed in the Materials section of this paper. The two streams exiting the vortex tube (**2** and **3**) run through similar but separate loops, and for purposes of brevity, only the vapor outlet stream (**2**) will be discussed. Once exiting the vortex tube, the temperature of the vapor outlet stream (**2**) is



measured using a thermistor (*Th 3*), and then passes through a cooler (*C 2*) to cool the stream to below room temperature. At this point, the vapor product stream is directed to a collection flask, or during a sampling event, to small (approximately 5 ml) sample collection vials. In the case of normal (non-sampling) operation, once entering the collection flask, the stream is mixed with the liquid stream outlet from the vortex tube (3) using a combination stirrer and cooling plate. The mixture is then returned to the feed storage flask using a pump.

### Gas Chromatograph

Samples collected from the experimental system were analyzed for component composition using a Varian Aerograph Model 1400 gas chromatograph. Data from the chromatograph output to a Shimadzu CR501 Chromatopac data processor. This processor performed qualitative component calculations using the "Area Normalization Method" discussed in the company literature (Shimadzu 12.1).

## Methods

### Parameters Under Investigation

In that one of the goals of this study was to come to a better understanding of the apparatus and its potential for achieving the desired separation, a series of parametric studies was developed in an attempt to investigate how performance was affected by changes in feed conditions and different combinations of vortex generators and sleeves.

As feed pressure and temperature are the variables which establish feed enthalpy, it may be useful to briefly look at enthalpy in the context of what is required theoretically for successful operation of our system.

From the enthalpies of the respective product streams, an enthalpy required in the feed stream to effect the desired separation can be back calculated. Since our flow rate is 0.1667 cc/s and is 21% cyclohexane, then to achieve a stream which is 90% cyclohexane and contains at least 50 % of the cyclohexane in the feed, the flow rate of the liquid product stream exiting the system must be 0.0175 cc/s (approximately 11.67 % of the feed). It is expected that, under optimum performance, all product leaving the "hot" end of the vortex tube will be 100 % liquid (no vapor entrainment), and that which leaves the "cold" end will be 100% vapor. Thus, for the sake of calculations, the temperatures of these streams can be assumed to be at the dew point and bubble point, respectively. Given these temperatures, the outlet pressure to which upon their exit these streams are exposed to (1 atmosphere), and the flow rates, the enthalpy of the liquid product stream is calculated to be -26.998 J/s, and that of the vapor product stream is -184.18 J/s. Given the enthalpies of the respective product streams, for a constant enthalpy process, an enthalpy of -211.178 J/s must be established in the feed stream to effect the desired separation. It was our intent, therefore, to investigate a range of enthalpies near -211.178 in an attempt to discern the effect feed enthalpy had on performance.

Upstream pressure in the heat exchangers is essential in establishing the enthalpy and quality of the feed which eventually enters the vortex tube. For this reason, it was necessary to conduct trials at several different upstream pressures in order to evaluate

system response and stability. To that end, we chose to test the system at 4, 6, 8, and 10 atmospheres in the heat exchangers, monitoring system performance and the effect on the feed pressure at the inlet of the vortex tube.

Ultimately, the pressure of the feed immediately upstream of the vortex tube is an important parameter. However, the pressure in this region was established by upstream conditions as well as the downstream resistance to flow. In other words, the pressure of the feed entering the vortex tube was a function of the enthalpy and quality of the feed upstream in the heat exchangers, as well as the diameter of the orifice in the Teflon<sup>®</sup> disk at the entrance to the vortex tube. Although we were unable to directly control the pressure in this region, depending on upstream conditions, we were able achieve "steady state" conditions with pressures in this region ranging from 15 to 35 psig, or 2.0075 to 3.368 atmospheres (depending on upstream conditions) by making the diameter of the orifice in the Teflon<sup>®</sup> disk 0.0135 inches.

Feed quality was established through controlled heating in the heat exchangers. For a given upstream pressure, trials were investigated which spanned the range from the bubble point to the dew point of the mixture. Like the situation for pressure, however, the quality of the feed at the inlet to the vortex tube was dependent on the conditions of the mixture flashing through the needle valve upstream. Referring to the previous discussion on relative volatility, by fixing the upstream temperature and pressure, for a given downstream inlet pressure, the temperature (and concomitantly the quality) of the feed in this inlet region are necessarily fixed. Thus, a given quality of the feed upstream in the heat exchangers was established, and the temperature and pressure of the feed in

the inlet region to the vortex tube was recorded. The quality of the inlet feed conditions was then determined using the flash simulator on ChemCAD® III, a procedure discussed in more detail below in the Calculations section of this chapter.

With respect to the generators and sleeves, a systematic approach was utilized to evaluate different combinations of the factory components and modified components. Using the respective components for the high (8 scfm) and low (2 scfm) flow rates allowed for 4 factory generators to be combined with each of two different factory sleeves, and tested over the pressure and quality ranges of interest. In a like manner, the modified generator ("GEN 1") was combined and tested with each of the factory sleeves, as well as the modified sleeve ("INSERT"). Finally, to round out the study, the modified sleeve was combined with several of the factory generators, and tested over the pressure and quality ranges of interest. Table 4 below lists the generator/ sleeve combinations evaluated in the study.

Combination	Generator	Sleeve
1	2 GC	2 T/S
2	2 GC	8 T/S
3	2 GR	2 T/S
4	2 GR	8 T/S
5	8 GC	2 T/S
6	8 GC	8 T/S
7	8 GR	2 T/S
8	8 GR	8 T/S
9	GEN 1	2 T/S
10	GEN 1	8 T/S
11	GEN 1	INSERT
12	2 GC	INSERT
13	2 GR	INSERT
14	8 GC	INSERT
15	8 GR	INSERT
16	NONE	NONE

**Table 4. Generator / Sleeve combinations evaluated in the current study.**

### Procedures

Steady state was achieved in the experimental system at a given feed enthalpy and quality in the manner previously discussed in the previous section of this chapter. Next, the flows of the respective streams exiting the vortex tube were adjusted (using the valve at the liquid outlet of the tube) to roughly reflect 15% of the product exiting the tube through the liquid outlet, and 85% of the product exiting the tube through the vapor outlet. After the flow adjustment, the system was allowed to come to steady operation again.

Once steady state was achieved, samples of the liquid and vapor streams were simultaneously taken. During the sampling period, all pressure and temperature readings of the system were recorded. Upon collection, the samples were immediately sealed, numbered, and placed in an ice bath to promote stability in the liquid phase until such time as they could be analyzed for mass and composition.

Several samples were taken for a given upstream temperature and pressure, after which the upstream conditions were changed and the process was repeated. As changing the generator and sleeve required partial system disassembly, this manner of testing allowed for investigation of a particular generator and sleeve combination over the pressure and temperature ranges of interest in an efficient manner.

Once collected and cooled, the sample vials were weighed, allowing for calculation of the mass of each stream sample, as well as the total product mass exiting the system.

Then, five microliters of each sample was injected into the gas chromatograph for compositional analysis.

### Calculations

For the purposes of this discussion, a "trial" is to be considered as one set of product stream samples collected using a specified generator and sleeve, at a specified inlet enthalpy and quality.

In order to evaluate system performance, several calculations were made on the data obtained for each trial, which included determination of the following: component and overall mass balances; cyclohexane enrichment in the liquid stream; n-pentane enrichment in the vapor stream; stage separation factor; recovery; and comparison with the case of an equilibrium flash. Each of these calculations will be addressed in more detail in the following discussion.

The law of conservation of mass can be restated for our purposes through the use of total and component material balances. The total material balance for our system can be written as:

$$F = L + V \quad (3.2)$$

where,  $F$  is the inlet stream feed rate,  $L$  is the liquid tails product rate, and  $V$  is the vapor heads product rate. In a similar fashion, a component mass balance around the system can be written for the species of interest as

$$Fz_i = Lx_i + Vy_i \quad (3.3)$$

where  $z_i$ ,  $x_i$ , and  $y_i$  represent the concentration of the species in the feed, liquid, and vapor, respectively. Application of Equations 3.2 and 3.3 to the data collected from the system ensured that there were no leaks, and that the system was indeed operating at steady state.

Having analyzed and recorded the compositions of the samples from a trial, determining the cyclohexane enrichment in the liquid stream and n-pentane enrichment in the vapor stream was as straightforward as computing the component composition difference between the feed and the respective product streams. Considering the degree of enrichment in this way allowed for (1) a "quick and dirty" method of comparing system performance among a series of trials for a fixed feed condition during system operation, (2) determining whether the system was operating at near steady state, and (3) determining to what extent (if any) the system was separating the components.

The stage separation factor, or relative volatility, was described earlier in this chapter, and defined in Equation 3.1. Calculating the stage separation factor allowed us to place a quantitative value on the separation achieved for each trial, and make comparisons on the performance given different operating conditions. Additionally, this calculation permitted a comparison to be made between the separation achieved for that trial, and the hypothetical separation which could be achieved under simple equilibrium flash conditions.

As mentioned previously, the ultimate goal of our part of the Phase Two investigation was to achieve a separation which resulted in the liquid stream exiting the vortex tube to have a composition of at least 90 % cyclohexane, coupled with at least 50

% recovery. Recovery, for our purposes, can be defined as the amount of cyclohexane reclaimed in the liquid product stream, and is given below in Equation 3.4.

$$R^{cyclo} = \frac{Lx_{cyclo}}{Fz_{cyclo}} \quad (3.4)$$

Finally, we used a computer-aided design (CAD) software package, ChemCAD<sup>®</sup> III, to provide reference data with which to compare the results of our trials. Simulating our system with this CAD package, we were able to input the upstream conditions and simulate a cascading flash: one flash through the needle valve to the region of the vortex tube inlet, and the other flash from the inlet of the vortex tube to atmospheric pressure at the exit. The relative volatility, component enrichment, and recovery could then be calculated for the simulated flash based on trial conditions, and the results compared with the actual trials.

It must be noted that for these calculations, atmospheric pressure was designated as 1 atm (0 psig). Atmospheric pressure in Bozeman MT varied at a level somewhat less than this (approximately 0.84 atm) during the period of time the trials were conducted, but standardization was necessary for making the calculations. It was recognized that this difference in pressure has a notable effect on the separation possible; however, the separation should actually be better when flashing to a lower pressure. Accordingly, the simulated flash to 1 atm would allow for a "worst case" scenario with which to compare our trial results.

As a final point, ChemCAD<sup>®</sup> III was used to provide data with which to compare the conditions indicated by the sensors and gauges following the flash through the needle



valve. A simulation was created using the software package which included a series of two flash vessels. The first one was intended to mimic the flash through the needle valve, from the conditions established in the heat exchangers to the conditions in the region immediately preceding the vortex tube. The second one was intended to mimic a flash through the vortex tube to atmospheric pressure. Providing the simulation with the feed temperature and pressure in the heat exchangers (and thus the enthalpy and quality), and specifying a pressure in the region immediately upstream of the vortex tube, the simulation calculated constant enthalpy flashes through the vessels, and in so doing, provided temperature data in the regions downstream of the heat exchangers with which to compare the measurements indicated by our sensors in these areas. Reasonable agreement between predicted and measured conditions was to provide some measure of confidence in the quality of the feed entering the vortex tube.

## CHAPTER 4

## RESULTS AND DISCUSSION

Procedural Findings

Initially, several trials were conducted to test the system at approximately 44.1, 73.5, 102.9, and 132.3 psig (four, six, eight, and ten atmospheres, respectively) upstream in the heat exchangers, which enabled us to qualitatively evaluate performance and stability. Figure 9, below, is a plot of enthalpy as a function of quality for these pressures.

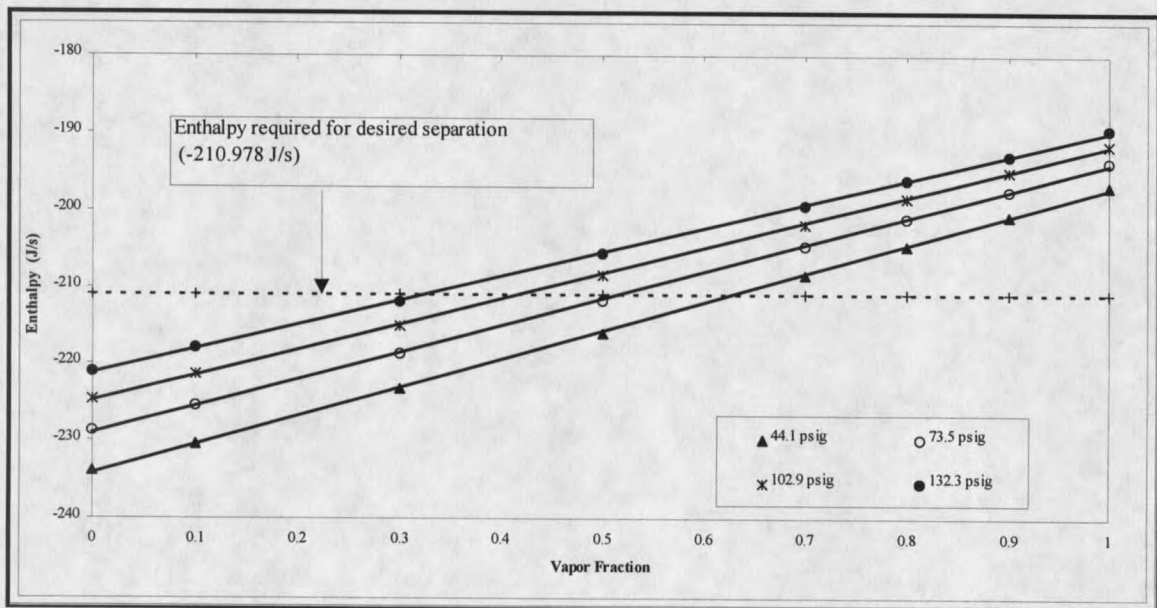


Figure 9. Enthalpy as a function of quality for several feed stream pressures.

Our intent was to establish a range of enthalpies near  $-211.178 \text{ J/s}$  (discussed in the previous chapter). Figure 9 demonstrates that for a given pressure, as vapor fraction is increased, enthalpy is also increased (becomes less negative). Likewise, for a given vapor fraction, enthalpy is increased as pressure is increased. For a given enthalpy, we found that the feed conditions established in the heat exchangers at the lower pressures produced feed conditions downstream (after flashing through the needle valve) which were more desirable, in that the maximum vapor fraction established in the feed stream at the entrance to the vortex tube was typically higher. As an example, the figure above shows that for an enthalpy in the heat exchangers of roughly  $-220 \text{ J/s}$ , the quality of the stream at  $132.3 \text{ psig}$  is less than  $10 \%$ , whereas for a pressure of  $44.1 \text{ psig}$ , the quality of the stream is roughly  $40 \%$ . Since the intent was to be able to investigate a range of quality in the feed to the vortex tube, and previous research suggested that this range be more toward the end of higher vapor content (Collins and Lovelace 304), Figure 9 indicated that the lower pressures of  $44.1$  and  $73.5 \text{ psig}$  in the heat exchangers would be desirable.

From an operational standpoint, we did note that the system fluctuated less at the "middle-range" pressures of  $73.5$  and  $102.9 \text{ psig}$ .

Therefore, based on enthalpy/quality concerns and ease of system control, we decided use a pressure of around  $73.5 \text{ psig}$  in the upstream region. This enabled us to test the various generator and sleeve combinations at the temperatures of  $108$ ,  $109$ ,  $110$ , and  $111$  degrees Celsius, which established an enthalpy range from approximately  $-205$

J/s at 111 degrees Celsius to approximately -220 J/s at 108 degrees Celsius. The use of the word "approximately" here is due to the fact that the pressure in the heat exchangers was not easily maintained at exactly 73.5 psig for all trials. Deviations of two or three tenths of a pound per square inch (guage) in either direction were common, but this did not have a significant impact on the enthalpy.

As a final note, a mass balance was performed on the results of each trial, as discussed in the previous chapter. Given the n-pentane composition as measured by the gas chromatograph in either of the product streams, along with the fraction of the feed leaving as that stream, the composition of this component in the other product stream was predicted using Equations 3.2 and 3.3. Comparing the difference, or deviation, between the measured and predicted compositions of both streams allowed for some degree of a quantitative analysis to be made as far as whether or not the system was operating at "steady state" during the trial.

We decided that if the error between the measured and predicted values of both streams in a trial exceeded an arbitrary threshold of 5%, the system was probably not operating at steady state, and the results from that trial were thrown out. It must be noted that there was a significant ( $> 50\%$ ) difference between the measured and predicted composition of the liquid stream for several trials. This discrepancy may very well be explained by the fact that in most of these instances, the amount of product leaving as liquid was very small compared to that leaving as vapor. As such, the predicted liquid composition was much lower than that which was actually measured. However, for many

of these trials the complementary error for the vapor stream composition was well below 5 %, and for that reason, we chose to retain the trial data.

Although an explicit presentation of the findings of this analysis will not be presented here, a sample of these calculations for several trials is included at the end of this paper, as Appendix A.

### Generator and Sleeve Performance

Each of the generator/sleeve combinations listed in the previous chapter were tested in the vortex tube. As a measure of “overall” generator/sleeve combination performance, the stage separation factor achieved by a given combination for each trial was discerned. The data was compiled and sorted by generator/sleeve combination, and for this “overall” analysis, evaluated irrespective of feed pressure, quality, and enthalpy tested in the trials. The generator/sleeve combinations were then ranked relative to maximum and average stage separation factor achieved. The results of this analysis are presented in Tables 5 and 6.

<u>Rank</u>	<u>Generator</u>	<u>Sleeve</u>	<u>Maximum Stage Separation Factor</u>
1	2 GC	INSERT	4.516
2	NONE	NONE	4.252
3	8 GR	8 T / S	3.726
4	8 GC	INSERT	3.443
5	8 GR	INSERT	3.329
6	GEN1	INSERT	3.264
7	GEN 1	8 T/S	3.194
8	8 GC	8 T/S	3.193
9	8 GC	2 T/S	3.174
10	2 GR	8 T/S	3.075
11	GEN 1	2 T/S	3.063
12	2 GC	2 T/S	3.041
13	2 GR	INSERT	3.025
14	8 GR	2 T/S	2.974
15	2 GR	2 T/S	2.922
16	2 GC	8 T/S	2.481
<b>CONSTANT ENTHALPY FLASH:</b>			<b>4.152</b>

**Table 5. Overall performance of the various generator/sleeve combinations, ranked by the maximum stage separation factor achieved for a particular combination. This includes the results over all ranges of feed conditions tested. Also indicated is the average value calculated for the trials under conditions of constant enthalpy equilibrium flash.**

Rank	Generator	Sleeve	Average Stage Separation Factor
1	NONE	NONE	3.214
2	8 GC	8 T/S	2.928
3	2 GC	INSERT	2.847
4	8 GR	8 T / S	2.788
5	2 GR	INSERT	2.694
6	8 GC	2 T/S	2.659
7	GEN1	INSERT	2.626
8	8 GR	2 T/S	2.597
9	GEN 1	2 T/S	2.499
10	2 GR	8 T/S	2.438
11	8 GR	INSERT	2.438
12	8 GC	INSERT	2.400
13	GEN 1	8 T/S	2.266
14	2 GC	2 T/S	1.943
15	2 GC	8 T/S	1.796
16	2 GR	2 T/S	1.471
CONSTANT ENTHALPY FLASH:			3.624

**Table 6. Overall performance of the various generator/sleeve combinations, ranked by the average stage separation factor achieved for a particular combination. This includes the results over all ranges of feed conditions tested. Also indicated is the average value calculated for the trials under conditions of constant enthalpy equilibrium flash.**

As defined in Equation 3.1, the stage separation factor depends on the composition of both product streams, and as such, provides a more insightful measure of the degree of separation achieved than looking simply at the cyclohexane increase in the liquid stream.

Table 5 indicates that at least on two occasions, the separation achieved in the vortex tube was better than that predicted for constant enthalpy equilibrium flash. Out of a total of 268 trials, these were the only two occasions where the trial stage separation factor was higher than the equilibrium flash. In both of these cases, the cyclohexane

concentration in the liquid stream was much lower than predicted (five to six percent lower). However, the n-pentane composition in the vapor stream was much higher than the case of the equilibrium flash, giving rise to the higher-than-flash stage separation factors. As a result, within experimental error, we cannot conclude with certainty that we are achieving a separation better than that predicted for an equilibrium flash.

It is particularly interesting to note on Table 5 that one of the two cases which exceeded flash expectations was when there was no generator and no sleeve present in the vortex tube, and the vortex tube was functioning as a simple "flash vessel," where the pressurized feed was allowed to expand and the phases separate when exposed to atmospheric pressure. Further, when considering Table 6, the case of no generator and no sleeve outperformed all of the other combinations tested in the experimental apparatus, and by a somewhat significant margin over the next "best" combination.

One possible accounting for these two exceptions, that we have considered is that, based on the n-pentane increase in the vapor, there may be some condensation taking place in the coolers (or the ends of the vortex tube as a result of heat transfer from the vortex tube to the coolers) which is assisting the separation in these cases. As one of the cases of improved separation factor includes the situation where there is no vortex generation device involved, and on average this configuration outperforms the rest of the combinations, it is fairly certain that vortex action can not be responsible for the results.

While several suggestions regarding the performance of our system can be made when considering the stage separation factor data, the most obvious interpretation of the



data is that the presence of a generator and sleeve in the vortex tube actually impeded the ability of our system to effect a separation in this two-phase feed mixture.

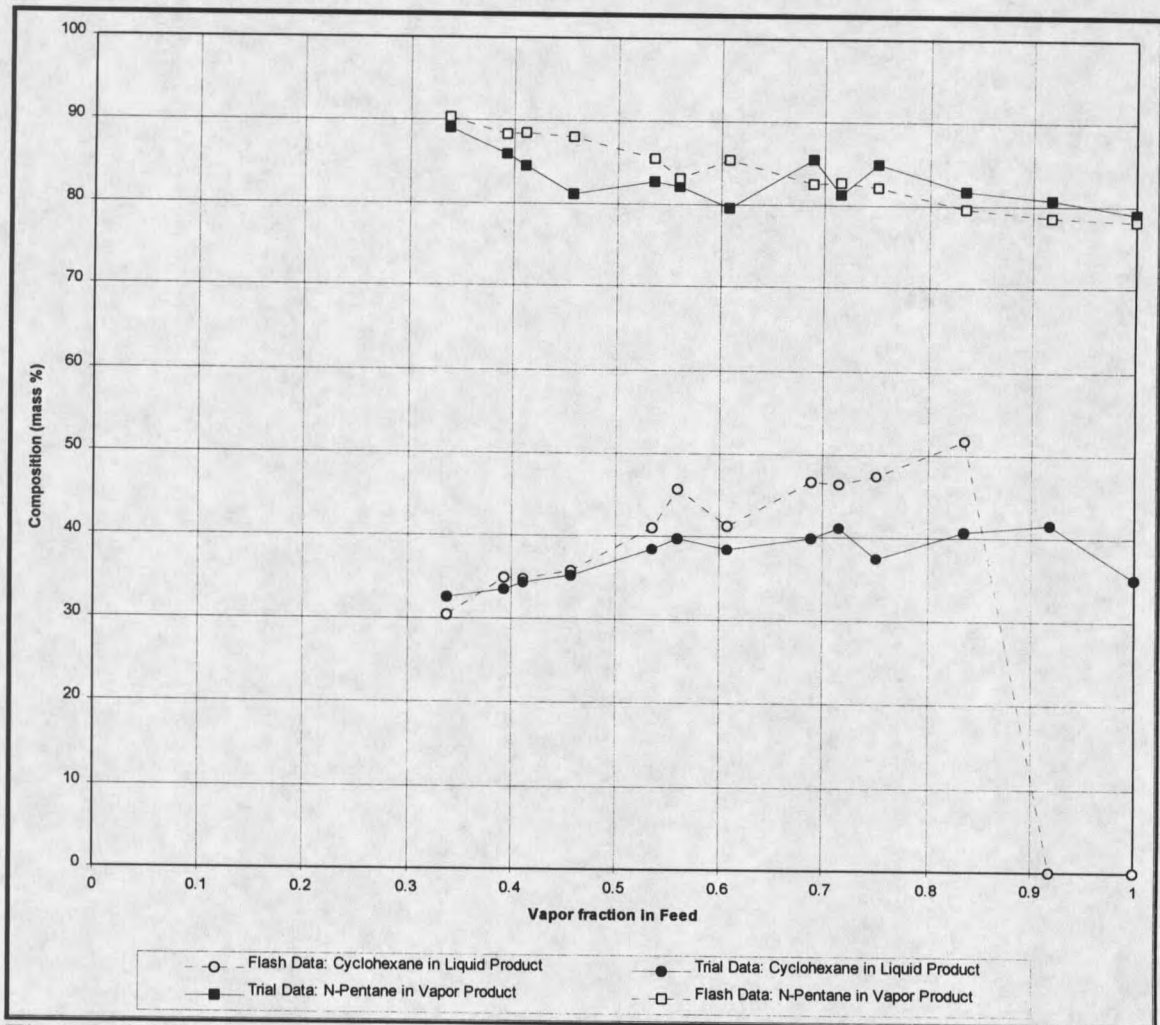
### Effects of Quality

As explained in the previous chapter, the pressure of the feed entering the vortex tube was dependent on the feed conditions upstream in the heat exchangers, and how quickly the feed could get through the orifice and into the tube. The small orifice in the Teflon<sup>®</sup> disk at the inlet to the vortex tube created a back pressure in the region between the heat exchangers and the tube, and consequently, we were able to observe feed pressures in the region between the needle valve and the vortex tube which ranged from 15 to 35 psig. In a few cases, pressures exceeding 35 psig were observed.

Pressure and temperature were used to establish the enthalpy and quality of the feed in the heat exchangers upstream, as previously described. Then, after a constant enthalpy flash through the needle valve, the quality of the feed at the entrance to the vortex tube could be determined by the pressure in this region. Therefore, it may be useful to explore the effect quality of feed had on the separations achieved in our system.

Figure 10, below, is a plot of concentration as a function of feed quality. The data was compiled for all of the trials, and sorted into groups which reflected a range of 5% quality. Then, the trial which displayed maximum cyclohexane increase in the liquid was chosen out of each group. Indicated in the figure are the maximum concentrations of cyclohexane in the liquid observed in the trials, along with the n-pentane concentrations

in the vapor for each trial selected. Also indicated with the trial data Figure 10 is the accompanying concentrations of each hydrocarbon which would occur under equilibrium flash conditions, as predicted by ChemCAD® III.



**Figure 10. Maximum values of component enrichment as a function of feed quality (irrespective of generator/sleeve combination and enthalpy).**

Figure 10 seems to indicate that the expected relation between increasing vapor fraction and increasing cyclohexane enrichment in the liquid stream was demonstrated by the experimental data. Also, there is a data point in this plot which indicates that the

separation effected by the vortex tube exceeded that which was predicted by the condition of simple equilibrium flash. This trial, it must be noted, was for the case where no generator and no sleeve were present inside the vortex tube.

Next, the maximum n-pentane enrichment in the vapor stream exceeded the enrichment predicted for the flash case for several data points taken from trials where the vapor fraction in the feed exceeded roughly 68 %. This trend is more interesting, and may deserve a bit more attention. N-pentane enrichment in the vapor stream higher than predicted by the case of equilibrium flash is curious, in that for most cases there was not a complementary enrichment of cyclohexane in the liquid above the flash prediction. Once again, we suspect that this could be due to some sort of partial or "differential" condensation of vapor in the liquid product cooler. Or perhaps, heat transfer from the tube to the coolers is causing a net decrease in the temperature of the vortex tube. Given that our system is operating at constant enthalpy, the latter is certainly indicated, in that the measured temperatures of the product streams are below that predicted by equilibrium flash conditions, and in some cases, well below the flash temperature. Whatever the cause, the simple observation to be made here is that the findings do little to support any conclusions that there is significant performance enhancement in our system beyond what is expected by simple equilibrium flash. Rather, the figure may serve to illustrate that with respect to changes in pressure and quality, our vortex tube is essentially functioning as a flash vessel, and a poor one at that when considering the objective of obtaining a liquid product stream which is significantly enriched in cyclohexane.

Finally, at feed quality in excess of 90 %, where the flash simulation predicted that no product should be leaving the system as liquid, the vortex tube produced a liquid stream cyclohexane composition which was among the highest overall values observed. The high concentrations can be accounted for, as in the limit, where the feed contains increasingly less liquid so that a very small but discrete amount of liquid remains after the flash, the liquid product stream will be maximally enriched in cyclohexane.

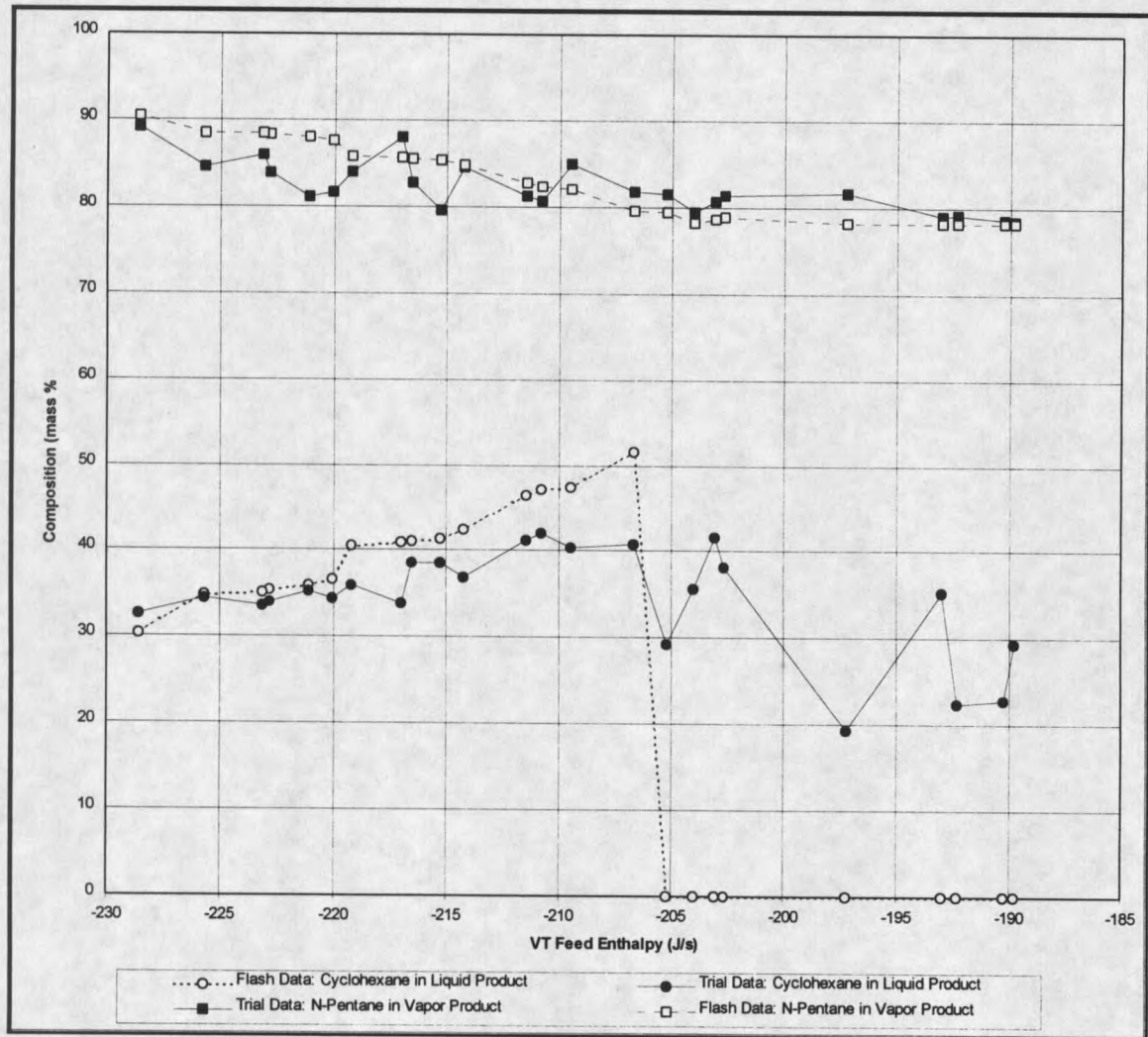
Additional plots were constructed to depict the performance of particular generator/sleeve combinations as a function of quality for the factory-built combination which effected the highest average stage separation factor, as well as a plot for the "best" combinations for each of the components we modified. Also, a plot was constructed for the case where the tube was functioning as a "flash vessel." In general, the combinations showed similar trends for the most part, in that as feed vapor fraction was increased there was a concomitant increase in cyclohexane enrichment in the liquid product. While for purposes of brevity these plots are not presented in the body of this paper, they are attached at the end of the document as Appendix B, should the reader wish to view them.

#### Effects of Enthalpy

An analysis was made of the trial data to determine the influence feed enthalpy had on the performance of our system.

Figure 11 is yet another plot which displays the results of trials which produced the maximum degree of component enrichment in the product streams as a function of feed conditions. In this figure, the feed condition analyzed is enthalpy, and where possible,

the data selected for representation were the 3 or 4 maximum values out of groups which spanned a range of 5 J/s, and were chosen irrespective of the generator/sleeve combination used.



**Figure 11. Maximum cyclohexane enrichment in the liquid product as a function of feed enthalpy, irrespective of generator/sleeve combination. Also depicted is the associated n-pentane composition in the vapor, as well as the predicted compositions of each component based on a constant enthalpy equilibrium flash.**

Beyond displaying some of the same trends that were evident in the analysis of feed quality, inspection of Figure 11 reveals a region of enthalpy where cyclohexane enrichment in the liquid product stream is maximum.

Further, Figure 11 reinforces the fact that the separations produced by our system mimic the general trends predicted by the flash simulation, but when considering the concentration of cyclohexane in the liquid, again the only occasions where the trial data was better than that predicted by equilibrium flash was (1) the case of the single trial using no generator and no sleeve, and (2) when the flash simulation predicted no liquid product given the feed conditions:

Again, with respect to the cases where the simulation predicted no liquid product several mechanisms could be responsible. As previously mentioned, there could exist partial or some sort of "differential" condensation of vapor in the liquid cooler.

Alternatively, it could be that vortex action inside the tube served to condense part of the product, although this is more than a little contraindicated by all other measurements of performance and enrichment. While the presence of a liquid product where there should be none could be explained by either of these mechanisms, the exact reasons for the occurrence are unknown to us at this time, and certainly deserve further attention.

Beyond this, the results of the enthalpy analysis (Figure 11) indicated that there was a region of feed enthalpy which produced the highest levels of cyclohexane enrichment in the liquid product. Also, as the feed enthalpy is increased and approaches this region (becomes less negative), the separations achieved increasingly fail to approach what is expected by equilibrium flash. As it happens, the region mentioned includes a feed

enthalpy of  $-211.178 \text{ J/s}$ , the minimum enthalpy required for the desired separation calculated in Chapter 3.

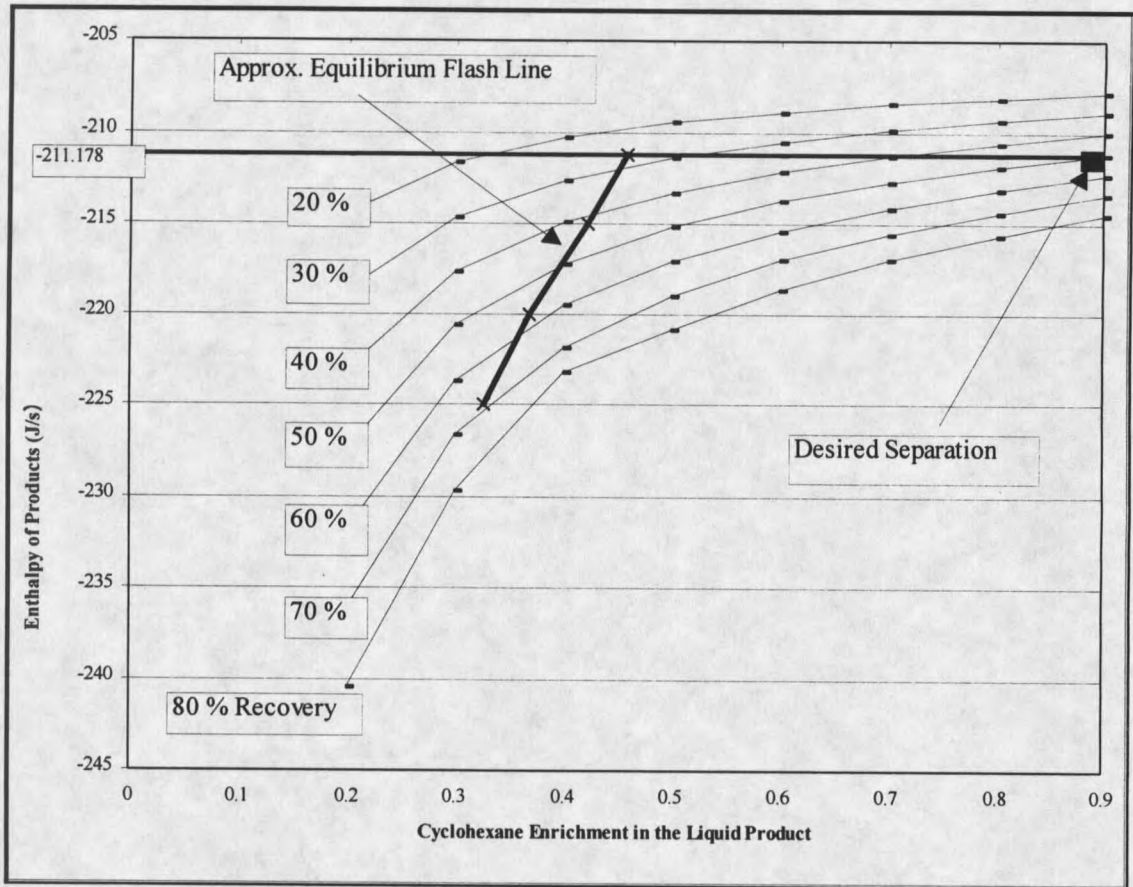
At this point it may be instructive to look at the effect of enthalpy as it relates to the separation we are trying to achieve, that is, a liquid stream enriched to 90 % cyclohexane which contains 50 % of the cyclohexane in the feed.

For the following analysis, several assumptions are made:

1. The overall process is at constant enthalpy (the sum of the product stream enthalpies is equal to the feed enthalpy).
2. Liquid product from the vortex tube is considered to be at the bubble point temperature, and the vapor product at the dew point.
3. Pressure of the product streams upon exiting the vortex tube is 1 atm.

Maintaining consistency with the First Law of Thermodynamics as it applies to our system (Equation 2.2), the enthalpies of both product streams were determined over the range of 20-90 % enrichment and 20-80 % recovery for the feed mixture of 21% cyclohexane and 79% n-pentane. The total flow rate of product was assumed to be that of our experiment,  $0.1667 \text{ cc/sec}$ . A plot was then constructed which portrays total product enthalpy as a function of enrichment for various constant recoveries, and is presented below as Figure 12.





**Figure 12. Combined enthalpy of the product streams as a function of cyclohexane enrichment for a range of constant recoveries for the system under investigation. Products are at 0 psig (1 atm) pressure.**

Indicated by a box on Figure 12 is the desired separation for this project, as well as the approximate equilibrium flash concentration for a given enthalpy. Inspection of this figure reveals that for a given feed enthalpy many separations are possible. For instance, a combined product enthalpy of  $-211.178 \text{ J/s}$  is consistent with separations which include:

1. 32.67 % enrichment / 20 % recovery
2. 45.72% enrichment / 26.92 % recovery (which is the equilibrium flash condition)



3. 51.5 % enrichment / 30 % recovery.
4. 90 % enrichment / 50 % recovery (the desired separation).

Although all of these separations are consistent with the First Law, use of the Second Law of Thermodynamics (Equation 2.4) allows for a determination to be made as to whether or not the separations are possible, and further, which separations are thermodynamically favored.

For a separation to be consistent with the Second Law, the total change in entropy ( $\Delta S_{\text{TOT}}$ ) must be greater than zero, as indicated below in Equation 4.1.

$$\Delta S_{\text{TOT}} = (S_p - S_F) > 0 \quad (4.1)$$

Here,  $S_p$  is the combined entropy of the product streams, and  $S_F$  is the entropy of the feed stream.

An analysis was performed which investigated the effect of feed pressure on Second Law feasibility for those separations described above which the First Law analysis indicated would be consistent with a feed enthalpy of -211.178 J/s. The entire results of this analysis, as well as a more detailed description of the stream properties, can be viewed in Appendix C. For the present interest, selected results of the Second Law analysis for these constant enthalpy (211.178 J/s) separations with respect to several different feed pressures and a feed flow rate of 0.1667 cc/sec are presented below in Table 7.

FEED PROPERTIES				Desired Separation			Eq. Flash Separation
$P_{Feed}$	$T_{Feed}$	VF	$S_F$	90 % ENR 50 % REC $S_P - S_F$	51.5 % ENR 30 % REC $S_P - S_F$	32.67 % ENR 20 % REC $S_P - S_F$	45.72 % ENR 26.92 % REC $S_P - S_F$
0	320.74	0.8744	0.1271	-0.00136	-0.00002	-0.00006	-0.00001
2.25	324.80	0.8557	0.1257	0.00004	0.00138	0.00134	0.00139
14.7	341.82	0.7715	0.1205	0.00524	0.00658	0.00654	0.00659
44.1	366.78	0.6290	0.1149	0.01084	0.01218	0.01214	0.01219
73.5	383.56	0.5168	0.1124	0.01334	0.01468	0.01464	0.01469
102.9	396.57	0.4165	0.1100	0.01574	0.01708	0.01704	0.01709
132.3	407.37	0.3212	0.1090	0.01674	0.01808	0.01804	0.01809

P : Pressure (psig)  
 T : Temperature (K)  
 $S_F$  : Entropy of Feed (J/K)  
 $S_P$  : Total Entropy of Products (J/K)  
 VF : Vapor Fraction in Feed  
 ENR : Cyclohexane Composition in the Liquid Stream  
 REC : Recovery (% of Feed Cyclohexane Recovered in the Liquid Stream)

**Table 7. Entropy analysis of several separations consistent with a constant enthalpy (-211.178 J/s) process, conducted for various feed pressures. Product stream pressure is 0 psig.**

The results in Table 7 reveal that not all of the separations indicated as consistent with the First Law are possible. Rather, the feed to the vortex tube must be at a suitably higher pressure than the products in order for there to be enough available energy to induce the separations. This is demonstrated in the table above for the case of the desired separation of 90 % enrichment and 50 % recovery. According to the analysis for this system where the product streams are exiting at 0 psig, feed pressures below about 2.25 psig do not possess enough available energy to make the desired separation.

Further, the results of this analysis demonstrate that it is the equilibrium flash separation which shows the greatest increase in entropy ( $S_P - S_F$ ) for the system, and thus, it is this separation which is thermodynamically favored over the other separations. To

achieve a separation better than the flash, something must induce temperature (and energy) separation. In the case of the present study, vortex formation is the mechanism responsible for this energy and temperature separation.

As mentioned previously, although we were able to measure some degree of temperature separation between the two product streams exiting the vortex tube, both of these temperatures were at best near, and typically below, that predicted for equilibrium flash. Analysis of the feed conditions with respect to any trend in the magnitude of this difference did not reveal any discernible trends. It has been speculated that there is some degree of heat transfer occurring between the coolers and the vortex tube, and perhaps this is the reason for the discrepancy between measured and predicted temperatures in the product streams.

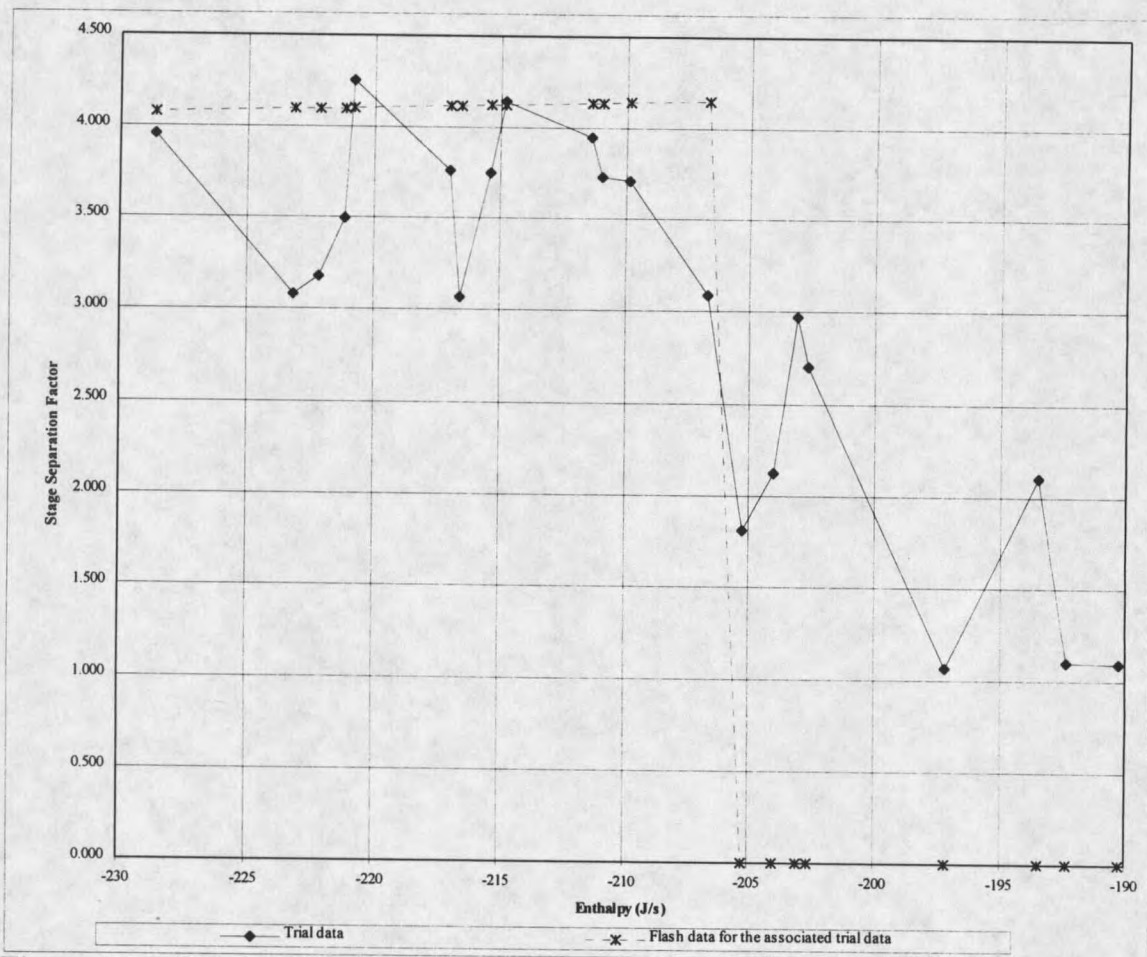
Be that as it may, for "better" separations in terms of recovery and enrichment, a temperature separation must occur which includes the vapor stream exiting at a temperature below the flash temperature, coupled with a liquid stream exiting at a temperature warmer than that predicted by equilibrium flash. The bottom line is that without a vortex occurring in the system, there is little chance of this occurring in our system. The fact that this investigation has seen little success in terms of separations better than that expected by the flash condition may very well support the determination that vortex formation is not achieved in the experimental apparatus.

However, in relating back to Figure 11, the data indicate that those trials where the cyclohexane in the liquid product stream seemed to more closely approach that predicted by the flash condition were those with lower (more negative) enthalpies. Figure 12, the

hypothetical separations plot, indicates that for a given enrichment, the more negative the enthalpy (to a point), the greater the recovery. Coupling the information indicated by these two plots with the information of Table 7 may give an indication of what is necessary for "better" separations; that is, the trends revealed in these figures suggests that lower (more negative) enthalpies should produce better separations in general, but this also must be coupled with additional temperature and energy separation induced by vortex action in order for the separation to be better than that of one equilibrium flash stage.

#### Overall Performance

The first analysis utilized to assess the overall performance of the vortex considered stage separation factor as a function of feed enthalpy. Recalling from the discussion in the previous chapter that stage separation factor is a measure of the relative ease of separating two components in a binary mixture by distillation, an analysis of the stage separation factor effected by the vortex tube provides a convenient means of placing a quantitative value on the separations achieved using this device. The results of this analysis are presented below in Figure 13.

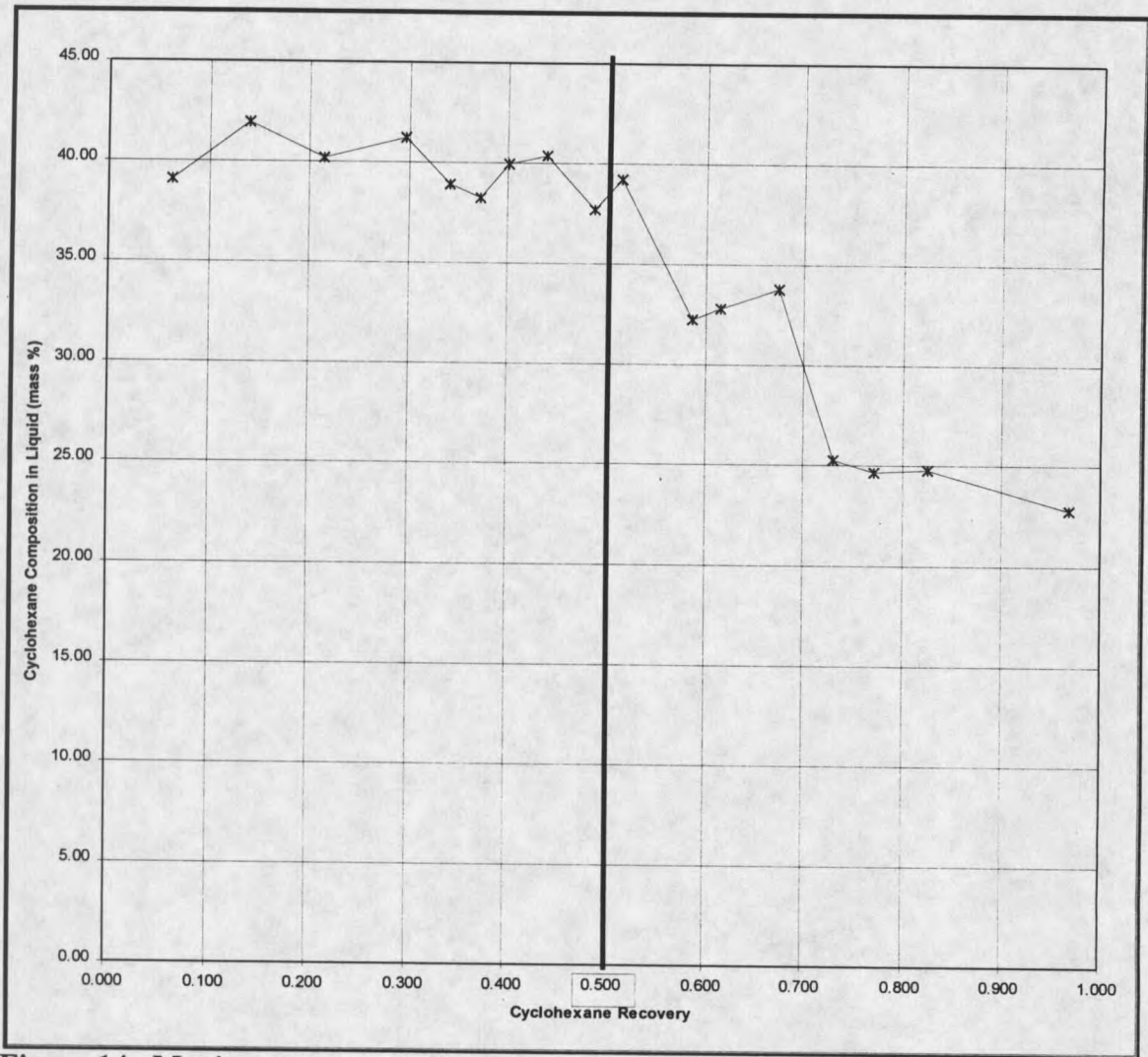


**Figure 13. Maximum stage separation factor achieved in the vortex tube as a function of feed enthalpy. Also indicated is the constant enthalpy equilibrium flash stage separation factor calculated for the respective trials.**

Figure 13 reveals a general trend in the trial data that as feed enthalpy is increased (becomes less negative), there is an accompanying decrease in the stage separation factor. Also indicated is the no-generator / no-sleeve case previously mentioned and discussed which achieves a stage separation factor greater than that predicted under equilibrium flash conditions.

Figure 13 also seems to indicate that the better separations were achieved at an enthalpy lower (more negative) than that which was predicted for the desired separation, -211.178, after which the stage separation factors achieved were much lower. Given the discussion in the previous section regarding the importance of feed enthalpy, the trend indicated in Figure 13 is perhaps evidence of the necessity that feed conditions with sufficient energy be established.

As a final assessment of overall vortex tube performance, a plot was constructed to depict maximum cyclohexane enrichment coupled with the degree of cyclohexane recovery (as described in the previous chapter) in the liquid stream as a result of the separation. Figure 14, below, represents the results of this analysis. To generate this plot, the raw data was sorted into groups comprising a range of 5 % recovery, and two or three trials from each group which represented the maximum level of enrichment were selected.



**Figure 14. Maximum amount of cyclohexane enrichment in the liquid stream as a function of recovery achieved using the vortex tube.**

Inspection of Figure 14 reveals that the trial separations did not even come close to meeting the ultimate objective of the study, which was to effect a separation of 90% cyclohexane enrichment coupled with 50% recovery. As indicated in the figure, the highest degree of enrichment observed (almost 42%) was coupled with a recovery of roughly 14 % of the cyclohexane originally introduced in the feed. Conversely, among



the separations which produced a recovery in excess of 50%, the highest degree of cyclohexane enrichment achieved in the liquid product stream was only 38%.

Coupled with the knowledge that neither of these instances surpassed the cyclohexane enrichment predicted for a simple equilibrium flash given their respective feed conditions, these data do not support any inferences that our investigation of the commercially available vortex tube was successful in terms of potential for usage as a separations device. Further, separation of hydrocarbons in this investigation came nowhere near the air separations Balepin reported in the literature (Air Collection Systems 417), which were the impetus for this study.

That being said, it must be emphasized that our attempts at separation of a two-phase binary hydrocarbon mixture using a vortex tube, from what we could discern in the literature, was unprecedented. It is reasonable to state, therefore, that the data obtained in this study can be considered very preliminary, and therefore, should not be used to suggest that the desired separation is unobtainable.

One of the goals of the study was to come to a better understanding of the operation of the vortex tube under conditions of two phase flow. Inasmuch as we were using a commercially available vortex tube designed for flows greatly exceeding those which we were introducing to it, it was discerned through the analyses that the degree of separation may in fact be quite dependent on feed conditions such as enthalpy and quality. That being the case, and if in fact a vortex was formed during the course of our trials, our data suggests that the vortex tube is not an overly flexible device in terms of handling feed conditions of a varying nature.



Furthermore, the study served to illuminate several areas in need of further investigation. For instance, analysis of the parametric studies on the generator and sleeve combinations leads us to ponder (at minimum) three major questions:

1. Were the generators at all successful in creating a sufficient degree of vortex flow, or did the 8 GC generator and 8 T/S sleeve perform better than the other combinations simply because their respective orifice dimensions provided less of an impedance to the flow, and resulted in less mixing?
2. If there was little or no vortex generation, was it due to generator/sleeve sizing problems, or is it that properties of the hydrocarbon system (such as molecule size) somehow prohibited vortex formation in the device?
3. If the generators did in fact create sufficient vortex flow, were the dimensions of the actual vortex tube excessively mismatched with our flowrate to allow for any positive effects the generators and sleeves may have had to be realized?

Directly resulting from the investigation, these questions, along with the trends and observations regarding the importance of feed conditions, provide at least a foundation for further efforts in assessing the potential of the vortex tube as a device for separating components in a mixture, be it cyclohexane from n-pentane, or oxygen from air for use in the propulsion systems of hypersonic flight vehicles.

## CHAPTER 5

## CONCLUSIONS

1. This was a preliminary investigation to determine whether a hydrocarbon mixture could be separated using a commercially available vortex tube. The desired separation was not achieved using the possible generator/sleeve combinations (designed for air flow rates between 2 and 8 scfm) which accompanied the unit.
2. Modifications to the generators and sleeves, based on extrapolation of generator and sleeve characteristic dimensions for different air flow rates, did not produce improvements in the performance of the system in terms of achieving separations better than that predicted for constant enthalpy equilibrium flash conditions.
3. All of the data to date seem to indicate that the best separations which have been achieved are only equivalent to that of one equilibrium flash stage. Many of the separations are poorer, indicating that the action of the vortex tube being tested produces mixing, entrainment, or other processes which reduce separation compared to an equilibrium flash.

## CHAPTER 6

## RECOMMENDATIONS FOR FUTURE RESEARCH

Investigations which specifically focus on addressing the questions presented in the discussion section may be instrumental in determining whether or not the surrogate hydrocarbon system is able to at least model prior studies of vortex tube air separations, and further, may lead to a better understanding of what might be necessary to achieve the desired separation.

This was a preliminary experiment using a commercially available vortex tube which was designed for air flow rates much greater than we were using. "Scaling-up" the system to match the minimum flow rate of the commercial vortex tube is both economically unfeasible and beyond the scope of a bench-scale project. In light of this, perhaps future investigations using a vortex tube which was custom designed for the flowrate of the system would allow for vortex formation, and thus, better separations with the hydrocarbon system.

Finally, in this preliminary investigation we were looking at a range of enthalpies to discern effects of this parameter on separation. It was suggested that establishment of feed conditions with sufficient energy is quite important in achieving any measure of separation over that achieved by equilibrium flash. Therefore, future efforts should be more focused on establishing feed conditions with sufficient energy, in terms of lower

(more negative) enthalpies, to achieve the desired separation, or at least increase the separation to levels beyond what is predicted for the equilibrium flash.

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APPENDICES

APPENDIX A

Sample Mass Balance Calculations

The following is a sample of the n-pentane mass balance calculations performed on each trial. Explanation of the procedure and screening methods used in this study can be found in Chapter 4 of this paper.

N-PENTANE MASS BALANCE											Predicted	Predicted	ERROR	ERROR		
Date	Trial	Gen	Sleeve	Feed Comp.	Measured Vap Comp	Measured Liq Comp	Feed mass	Vapor mass	Liquid mass	Predicted Vap Comp based on Liq Comp	Predicted Liq Comp based on Vap Comp	Vap Comp. (meas.-pred)	Liq Comp. (meas.-pred)	% ERROR Vap Comp	% ERROR Liq Comp	
4/13/98	1	2 GC	2 T/S	0.788	0.8395	0.6342	8.04	7.14	0.9	0.8074	0.3794	0.0321	0.2548	3.21	<b>25.48</b>	
	2	2 GC	2 T/S	0.788	0.8359	0.6263	6.50	5.34	1.16	0.8231	0.5675	0.0128	0.0588	1.28	5.88	
	3	2 GC	2 T/S	0.788	0.8335	0.748	10.70	5.55	5.15	0.8251	0.7390	0.0084	0.0090	0.84	0.90	
	4	2 GC	2 T/S	0.788	0.8018	0.7807	6.13	4.63	1.5	0.7904	0.7454	0.0114	0.0353	1.14	3.53	
	5	2 GC	2 T/S	0.788	0.8045	0.7247	9.79	9.19	0.6	0.7921	0.5353	0.0124	0.1894	1.24	<b>18.94</b>	
	6	2 GC	2 T/S	0.788	0.8143	0.619	8.98	8.5	0.48	0.7975	0.3223	0.0168	0.2967	1.68	<b>29.67</b>	
	7	2 GC	2 T/S	0.788	0.7875	0.7589	5.68	5.08	0.6	0.7914	0.7922	-0.0039	-0.0333	0.39	3.33	
4/15/98	1	8 GC	8 T/S	0.7855	0.846	0.672	5.56	3.76	1.8	0.8398	0.6591	0.0062	0.0129	0.62	1.29	
	2	8 GC	8 T/S	0.7855	0.8453	0.6312	9.08	8.26	0.82	0.8008	0.1831	0.0445	0.4481	4.45	<b>44.81</b>	
	3	8 GC	8 T/S	0.7855	0.8174	0.592	8.06	6.8	1.26	0.8214	0.6133	-0.0040	-0.0213	0.40	2.13	
	4	8 GC	8 T/S	0.7855	0.8143	0.5979	10.85	9.61	1.24	0.8097	0.5623	0.0046	0.0356	0.46	3.56	
	5	8 GC	8 T/S	0.7855	0.8125	0.5878	9.48	8.02	1.46	0.8215	0.6372	-0.0090	-0.0494	0.90	4.94	
	6	8 GC	8 T/S	0.7855	0.8068	0.5802	11.28	10.47	0.81	0.8014	0.5102	0.0054	0.0700	0.54	<b>7.00</b>	
	7	8 GC	8 T/S	0.7855	0.8104	0.6107	8.66	7.03	1.63	0.8260	0.6781	-0.0156	-0.0674	1.56	<b>6.74</b>	
	8	8 GC	8 T/S	0.7855	0.8065	0.5845	11.00	9.93	1.07	0.8072	0.5906	-0.0007	-0.0061	0.07	0.61	
	9	8 GC	8 T/S	0.7855	0.801	0.5986	8.78	6.96	1.82	0.8344	0.7262	-0.0334	-0.1276	3.34	<b>12.76</b>	
4/17/98	1	2 GR	8 T/S	0.785	0.9054	0.7725	8.88	0.75	8.13	0.9205	0.7739	-0.0151	-0.0014	1.51	0.14	
	2	2 GR	8 T/S	0.785	0.8271	0.7645	7.61	2.12	5.49	0.8381	0.7687	-0.0110	-0.0042	1.10	0.42	
	3	2 GR	8 T/S	0.785	0.8224	0.7448	6.62	2.86	3.76	0.8379	0.7566	-0.0155	-0.0118	1.55	1.18	
	4	2 GR	8 T/S	0.785	0.8318	0.7158	6.41	3.81	2.6	0.8322	0.7164	-0.0004	-0.0006	0.04	0.06	
	5	2 GR	8 T/S	0.785	0.8281	0.6696	5.73	4.18	1.55	0.8278	0.6688	0.0003	0.0008	0.03	0.08	
	6	2 GR	8 T/S	0.785	0.8278	0.6358	6.15	4.48	1.67	0.8406	0.6702	-0.0128	-0.0344	1.28	3.44	
	7	2 GR	8 T/S	0.785	0.8317	0.6164	7.60	5.73	1.87	0.8400	0.6419	-0.0083	-0.0255	0.83	2.55	
	8	2 GR	8 T/S	0.785	0.8187	0.6199	6.09	4.27	1.82	0.8554	0.7059	-0.0367	-0.0860	3.67	<b>8.60</b>	
	9	2 GR	8 T/S	0.785	0.8139	0.6173	6.43	5.38	1.05	0.8177	0.6369	-0.0038	-0.0196	0.38	1.96	
	10	2 GR	8 T/S	0.785	0.813	0.6041	7.81	5.96	1.85	0.7763	0.6948	0.0367	-0.0907	3.67	<b>9.07</b>	
4/22/98	1	2 GC	8 T/S	0.7884	0.831	0.7507	6.64	4.33	2.31	0.8085	0.7085	0.0225	0.0422	2.25	4.22	
	2	2 GC	8 T/S	0.7884	0.8171	0.7133	5.58	3.14	2.44	0.8468	0.7515	-0.0297	-0.0382	2.97	3.82	
	3	2 GC	8 T/S	0.7884	0.803	0.7068	7.73	4.76	2.97	0.8393	0.7650	-0.0363	-0.0582	3.63	<b>5.82</b>	
	4	2 GC	8 T/S	0.7884	0.8111	0.7641	7.01	4.61	2.4	0.8011	0.7448	0.0100	0.0193	1.00	1.93	
	5	2 GC	8 T/S	0.7884	0.8112	0.6746	9.27	8.18	1.09	0.8036	0.6173	0.0076	0.0573	0.76	5.73	
	6	2 GC	8 T/S	0.7884	0.8076	0.7102	6.18	5.65	0.53	0.7957	0.5837	0.0119	0.1265	1.19	<b>12.65</b>	
	7	2 GC	8 T/S	0.7884	0.7973	0.6132	4.41	4.18	0.23	0.7980	0.6267	-0.0007	-0.0135	0.07	1.35	
	8	2 GC	8 T/S	0.7884	0.7986	0.713	6.18	4	2.18	0.8295	0.7697	-0.0309	-0.0567	3.09	5.67	
4/27/98	1	2 GC	2 T/S	0.788	0.827	0.792	6.36	1.99	4.37	0.7792	0.7702	0.0478	0.0218	4.78	2.18	
	2	2 GC	2 T/S	0.788	0.867	0.81	3.57	0.5	3.07	0.6529	0.7751	0.2141	0.0349	<b>21.41</b>	3.49	
	3	2 GC	2 T/S	0.788	0.836	0.796	5.66	4.34	1.32	0.7856	0.6302	0.0504	0.1658	<b>5.04</b>	<b>16.58</b>	
	4	2 GC	2 T/S	0.788	0.836	0.699	7.17	4.37	2.8	0.8450	0.7131	-0.0090	-0.0141	0.90	1.41	
	5	2 GC	2 T/S	0.788	0.827	0.707	8.01	5.55	2.46	0.8239	0.7000	0.0031	0.0070	0.31	0.70	
	6	2 GC	2 T/S	0.788	0.838	0.674	3.97	3.18	0.79	0.8163	0.5867	0.0217	0.0873	2.17	<b>8.73</b>	
	7	2 GC	2 T/S	0.788	0.828	0.713	6.91	4.79	2.12	0.8212	0.6976	0.0068	0.0154	0.68	1.54	
	8	2 GC	2 T/S	0.788	0.816	0.776	2.99	2.39	0.6	0.7910	0.6765	0.0250	0.0995	2.50	<b>9.95</b>	
	9	2 GC	2 T/S	0.788	0.834	0.684	4.18	3.51	0.67	0.8079	0.5470	0.0261	0.1370	2.61	<b>13.70</b>	
	10	2 GC	2 T/S	0.788	0.827	0.687	4.16	3.4	0.76	0.8106	0.6135	0.0164	0.0735	1.64	<b>7.35</b>	
	11	2 GC	2 T/S	0.788	0.811	0.659	4.08	3.19	0.89	0.8240	0.7056	-0.0130	-0.0466	1.30	4.66	
	12	2 GC	2 T/S	0.788	0.817	0.724	4.03	3.51	0.52	0.7975	0.5923	0.0195	0.1318	1.95	<b>13.18</b>	
	13	2 GC	2 T/S	0.788	0.817	0.676	3.87	2.86	1.01	0.8276	0.7059	-0.0106	-0.0299	1.06	2.99	
4/28/98	1	8 GR	2 T/S	0.793	0.867	0.759	3.72	1.75	1.97	0.8313	0.7273	0.0357	0.0317	3.57	3.17	
	2	8 GR	2 T/S	0.793	0.849	0.735	3.91	2	1.91	0.8484	0.7344	0.0006	0.0006	0.06	0.06	
	3	8 GR	2 T/S	0.793	0.855	0.691	3.97	2.44	1.53	0.8570	0.6941	-0.0020	-0.0031	0.20	0.31	
	4	8 GR	2 T/S	0.793	0.854	0.728	3.86	2.4	1.46	0.8325	0.6927	0.0215	0.0353	2.15	3.53	
	5	8 GR	2 T/S	0.793	0.859	0.683	3.47	2.78	0.69	0.8203	0.5271	0.0387	0.1559	3.87	<b>15.59</b>	
	6	8 GR	2 T/S	0.793	0.859	0.672	3.40	2.08	1.32	0.8698	0.6890	-0.0108	-0.0170	1.08	1.70	
	7	8 GR	2 T/S	0.793	0.843	0.672	4.02	2.94	1.08	0.8374	0.6569	0.0056	0.0151	0.56	1.51	
	8	8 GR	2 T/S	0.793	0.844	0.655	4.14	3.02	1.12	0.8442	0.6555	-0.0002	-0.0005	0.02	0.05	
	9	8 GR	2 T/S	0.793	0.836	0.642	3.35	2.62	0.73	0.8351	0.6387	0.0009	0.0033	0.09	0.33	
	10	8 GR	2 T/S	0.793	0.844	0.648	3.61	3.09	0.52	0.8174	0.4899	0.0266	0.1581	2.66	<b>15.81</b>	

APPENDIX B

Plots of Composition as a Function of Quality for Selected  
Generator and Sleeve Combinations

