# THE EFFECT OF ULTRASONIC VIBRATION
# ON THE MASS TRANSFER IN A
# PACKED COLUMN

BY

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A THESIS

PRESENTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE IN CHEMICAL ENGINEERING

AT

NEWARK COLLEGE OF ENGINEERING

Newark, New Jersey

1972

APPROVAL OF THESIS

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FACULTY COMMITTEE

APPROVED:

NEWARK, NEW JERSEY

1972

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## ABSTRACT

The object of this research was to investigate the possibility of using externally supplied ultrasonic vibration to surface of a packed distillation column operating at total reflux to improve the separation. The apparatus used for this experimentation consisted of a 2 inch ID Pyrex column having three pairs of ultrasonic transducers epoxied equidistance along the external surface of the column. Each pair of transducers was driven separately by a 50 watt amplifier/ power supply and a sine/square wave generator.

There were three types of binary mixtures covered during experimentation: minimum boiling azeotropes, maximum boiling azeotropes and full range mixtures. In all cases the use of ultrasonic vibrations increased the composition of the overhead when compared with the normal operation. The principles which govern this improvement in separation are not well defined but can be partially explained by a combination of the following:

1. The velocity of the vapor and its direction are affected by the generation of high frequency sound waves and shock waves caused by caviation of the liquid.
2. The liquid loading as well as the path of the descending liquid are modified by the caviation of the liquid.

3. The arrangement of the packing is altered during ultrasonic operation which is evidenced by the presence of broken berl saddles in the areas of the transducers.

The above mentioned conditions are probably only a few of the many phenomena which occur in this quasi-steady state process. Only further experimentation can answer the questions which this experimentation has uncovered.

# PREFACE

Because commercial distillation equipment is usually limited by reboiler and/or condenser duty or constant boiling mixtures which may occur, some other process must be found to increase the efficiency of separation without drastically increasing either initial cost or utilities.

The purpose of this thesis is to investigate the possibility of using ultrasonic vibration to improve the separation of a packed distillation column operated at total reflux. The author will make no attempt to explain the results from a strictly thermodynamic or thermophysical standpoint; however, a critical evaluation of each system as well as recommendations for further study will be presented.

# ACKNOWLEDGEMENT

I would like to thank my advisor Dr. A. J. Perna, as well as Jerry Minter of the Components Corporation and Dr. R. H. Rose, for their guidance and assistance in procuring the equipment and laboratory space for my experimentation.

The funds for the experimentation were provided from a grant under Title IV of the National Defense Education Act.

I would also like to thank Barbara Lombardi and Karen Wagner for providing secretarial assistance and my employer, The Lummus Company, for giving me the opportunity to write portions of this text during working hours.

Especially, I would like to thank my parents who provided the incentive for me to complete my graduate studies even though they had been interrupted by a tour of duty with the United States Army, Republic of Vietnam.

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# THEORY OF PACKED COLUMNS

## 1. Equipment

Packed columns are used throughout the chemical process industries because they are an efficient and economical method of contacting liquids and vapors. A simplified diagram of a packed column is shown in Figure 1. In packed columns used for continuous countercurrent contacting operations, a vertical shell is filled with an inert material having a large surface to volume ratio.

The liquid phase $L_0$ enters the top of the column and is distributed over the upper surface of the packing by spray nozzles or weir distributors. The vapor phase $V_0$ enters the bottom of the column and rises through the voids of the packing where it contacts the descending liquid.

The packing can be made of any inert material, usually ceramic, metal or plastic. The packing used will differ depending on the service, but it should have the following general characteristics.(1)

a. A large wetted surface per unit volume to provide a large interfacial area for phase contacting.

b. A large void volume to allow a tortuous path for the ascending vapor with minimum pressure drop.

c. A porous surface to hold up the descending liquid for a longer resonant time.

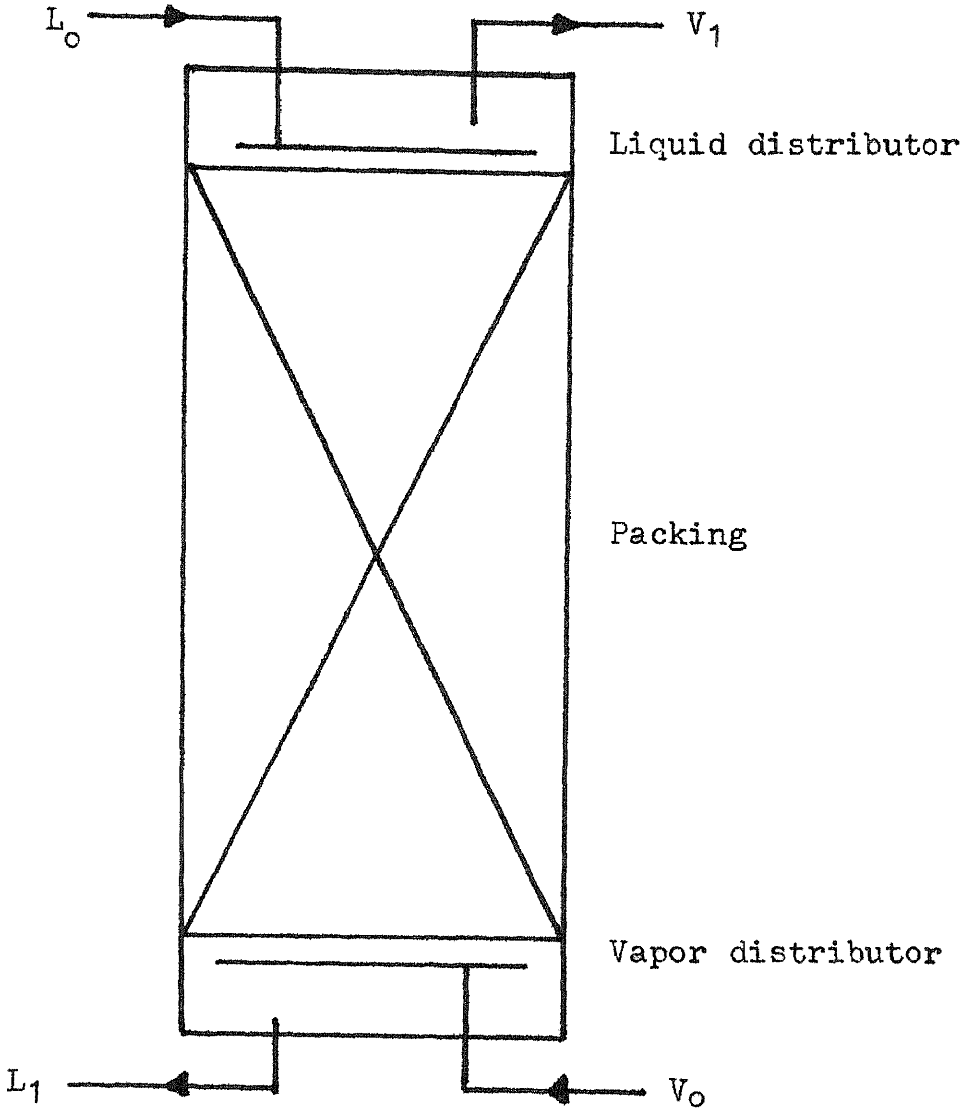


Figure 1. Simplified Diagram of a Packed Column

d. A low bulk density so the weight of packing does not become prohibitive.

e. Relatively low initial and operating costs.

## 2. Design

There are many companies involved in the production of packed columns for use in the chemical process industries. The leaders in the field are Norton (formerly U.S. Stoneware Inc.) and Koch; each has published extensive data on specific systems of interest. They have also developed experimental relationships which can be used to design a packed column for any service as a function of the desired loadings of liquid and vapor and the physical properties of the components.

Many theoretical approaches have been given to explain the mass transfer in a packed column. One of the first and probably the most significant article was authored by T. H. Chilton and A. P. Colburn in 1935.(2) In the article they defined, by the use of graphical integration, the measure of the difficulty of separation called the number of transfer units. Also defined was the height of a transfer unit which is the necessary amount of contacting needed to accomplish the enrichment of one phase equal to the driving force in the same phase.

Recently there have been many simplications and modifications(3)-(12) made to this technique, but it still serves today as the most rigorous method of design. With the advent of the computer this rigorous method is easily handled in a matter of seconds.

No attempt will be made in this thesis to treat the dynamics of a packed column from a theoretical approach; however, the effect of ultrasonic vibrations on a column of fixed design will be investigated.

# THEORY OF ULTRASONICS

## 1. Ultrasonic Waves(13)

Ultrasonic waves are sound waves propagating in a media at a frequency above the audible range, roughly defined as 20-20,000 cycles/second. This energy is mechanically transmitted in the form of an elastic wave through a media, either fluid or solid at a velocity independent of the frequency and amplitude, but dependent on the physical properties of the media. Because they are inelastic, fluids cannot propagate shear waves; however, compressional waves are readily transmitted in both fluids and solids. This principle will be employed in the experimental section of this thesis.

A sonic wave is a series of compression and rearification zones which travel with a characteristic amplitude, frequency and velocity. The pressure produced by this unidirectional wave can be expressed as:

$$P = P_0 + P_1 \sin 2\pi f (t - x/c) \qquad \text{[equation 1.]}$$

where $P$ = total instantaneous pressure in the media

$P_0$ = static pressure in the media

$P_1$ = magnitude of the pressure fluctuation

$f$ = frequency of the wave

$t$ = time from reference

$x$ = distance along some direction

$c$ = velocity of propagation

The power associated with this wave is called the sonic intensity and expressed in units of power per unit area.

$$I = P_1^2/2\rho c \qquad \text{[equation 2.]}$$

where $I$ = sound intensity
$\rho$ = density of the media

Because the molecules in a fluid are free to undergo vibration, they will vibrate back and forth in the same direction as a propagating wave is traveling. The velocity of each particle is directly proportional to the sound pressure:

$$= \frac{P_1}{c} \sin 2\pi f\ (t-H_c) \qquad \text{[equation 3.]}$$

The specific acoustic impedance is defined as the ratio of sound pressure to particle velocity and at high frequencies in the ultrasonic range is only dependent on the media.

2. <u>Sonic Generators</u>(14)

Sonic generators fall into two broad classes:

a. Fluid current interruption devices.
   1) Whistles and other gas current interrupting devices.
   2) Valve devices, such as sirens and vibrating reed-type devices.

b. Piston devices.
  1) Mechanical drive.
  2) Electrical drive.
    a) Electromagnetic
    b) Magnetostriction
    c) Piezoelectric

There are a variety of generators available depending on the frequency range and specific acoustic impedance required. Because it was desirable to operate in the 20 Kcps to 100 Kcps range and at a high specific acoustic impedance, a piezoelectric transducer was used as the sonic generator.

Figure 2 shows the spectrum of sound in gases (vapors). Because gases cannot support tension, there is an upper intensity level which cannot exceed ambient pressure. At any appreciable distance from the generator the sound energy is diffused over a larger area and consequently there will be a decrease in intensity.

Figure 3 shows the spectrum of sound in liquid assuming the ambient pressure is atmospheric. For sound intensities above approximately 0.6 watts/cm$^2$ cavitation will occur. Cavitation is the formation and violent collapse of small bubbles or cavities in the liquid caused by localized changes in pressure. The negative pressure portion of the sound wave causes vaporization and the bubbles of vapor

Figure 2. Spectrum of Sounds that can be Produced in Gases

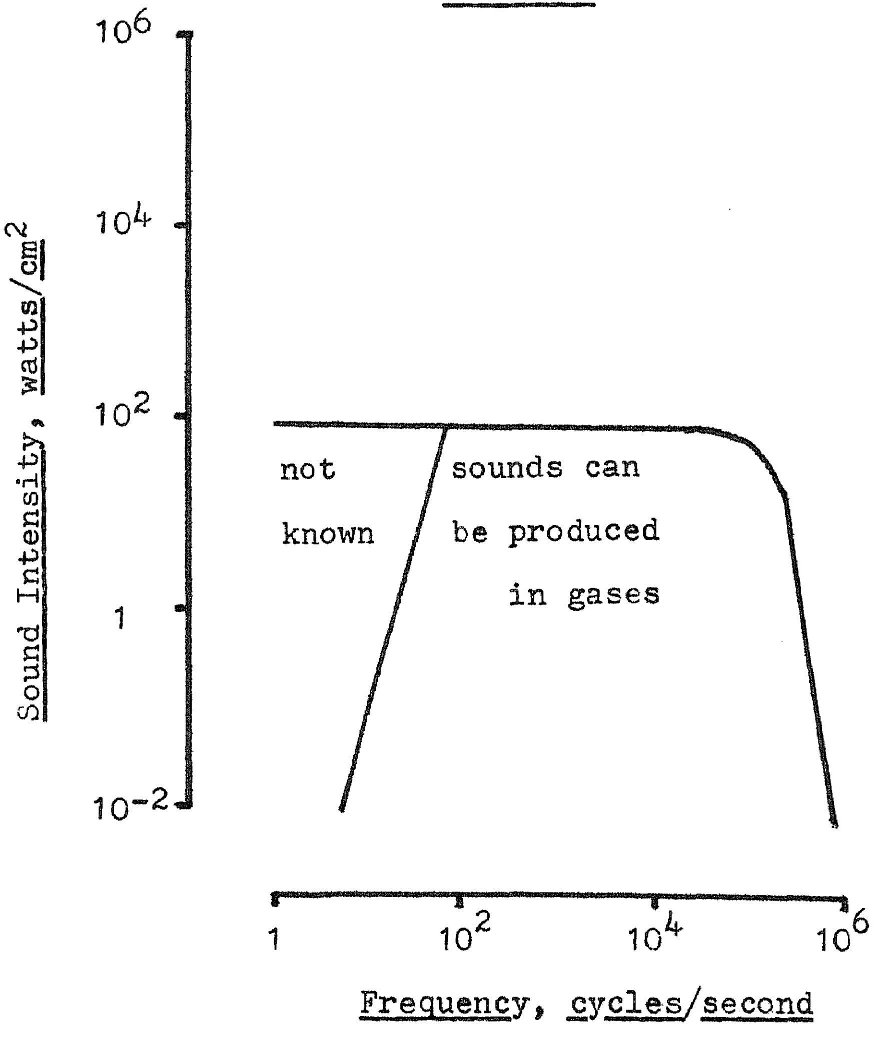
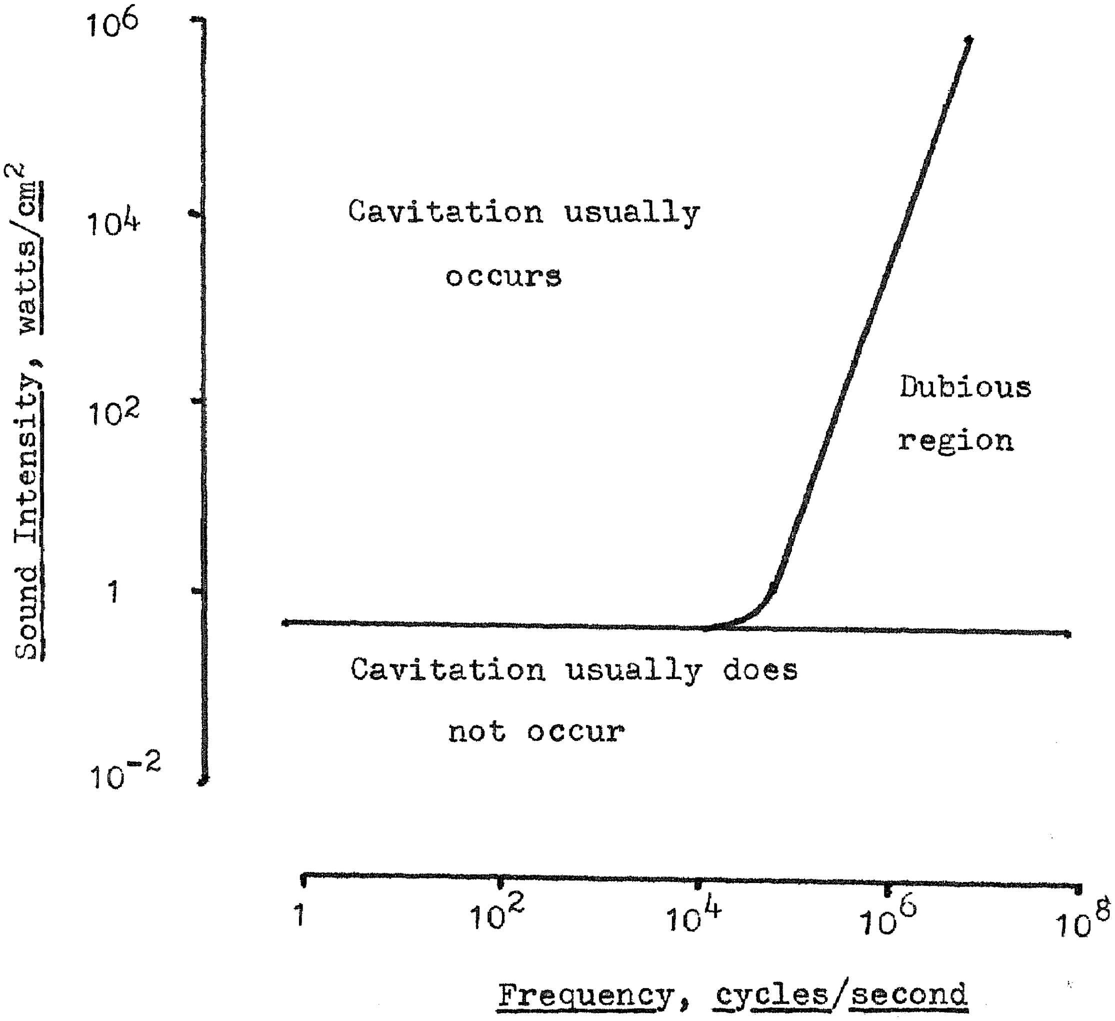


Figure 3. Spectrum for Liquids at Atmospheric Pressure



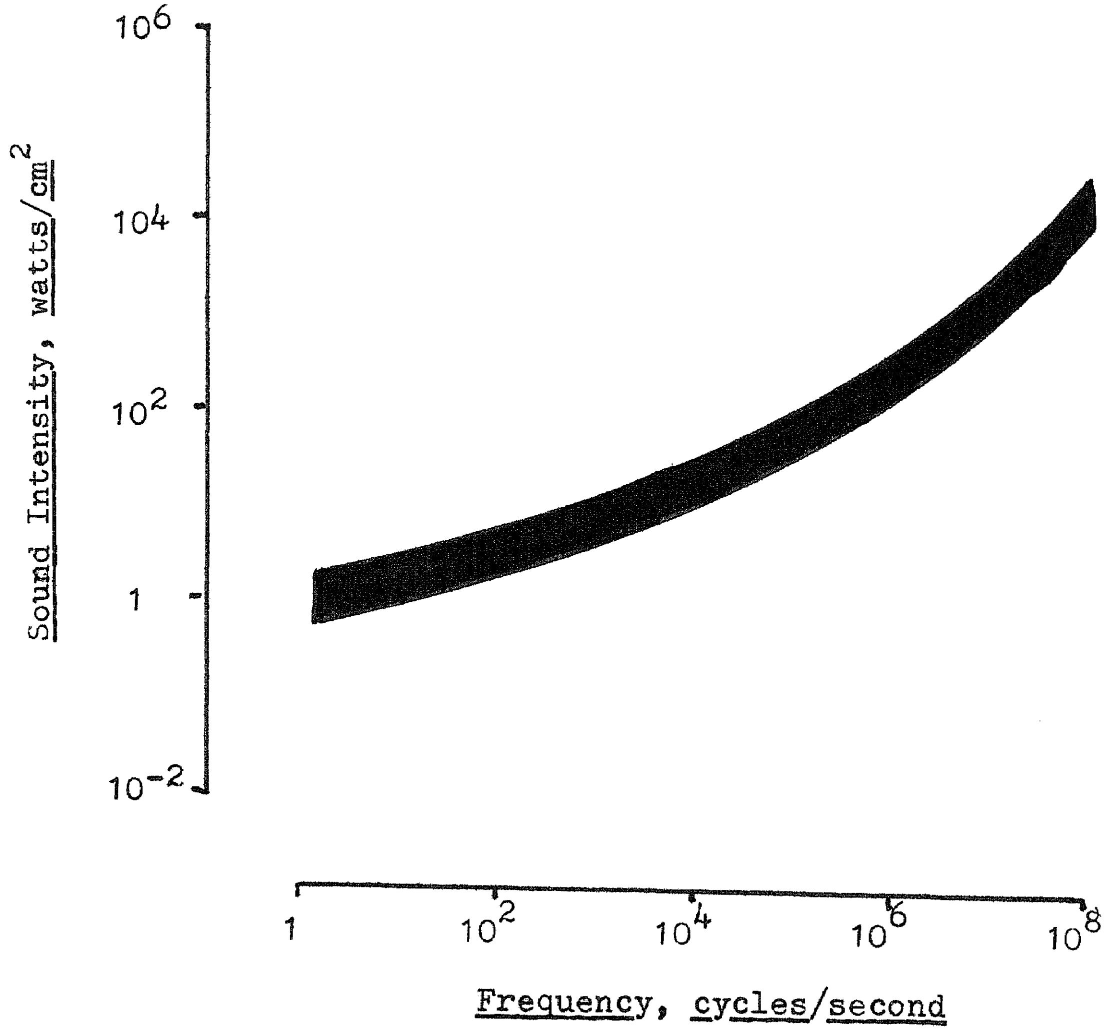
act as points for further tearing apart of the liquid to form larger cavities. When the positive position of the wave is reached, these cavities collapse violently causing shock waves in both the liquid and vapor phases.

Piezoelectric transducers are able to produce intensities above the cavitation level. The maximum power output of a transducer is determined by the area of the transducer because the peak sound intensity is limited. Figure 4 gives the peak sound intensity obtainable as a function of the frequency of the sound wave. Even if the maximum intensity of the transducer lies in the cavitation region, this phenomenon may not occur because of the formation of bubbles which obstruct the path of the sound wave.

## 3. Industrial Uses

There have been many industrial applications of ultrasonic vibrations since the first time it was mentioned in the literature(15); however, until the end of World War II little of the technology was put to practical use. During this period many technical publications appeared giving data on yields and power consumption which looked on the surface to be very promising.(16) Major applications were made in ultrasonic dust precipitation plants, but the failure of these units to reach the theoretical optimum caused reservations on the part of many industrialists. Since then numerous studies have

Figure 4. Peak Sound Intensity Obtainable at the Focus of a Sound System as a Function of Frequency



been made to improve the design of these systems. Although power consumption is still the major drawback, the units are able to handle very small particles and operate over a wide temperature range.

Until the late 1950's progress in the ultrasonic field was restricted to aerosols.(17) At that time investigations were made to determine what effect pulsation and vibration had on the rate of diffusion processes. The first studies were made by a group of Russians,(18) who studied what influence the pulsating motion of a liquid had on the rate of dissolution of a solid suspended in the liquid. Another group of Russians made subsequent studies which correlated the hydraulic resistance of a layer of zinc dust as a function of frequency. As interest grew they extended their work to study the rate of heat transfer in layers of free-flowing materials subjected to pulsation.(19)

## 4. Past Experimentation

The only application of ultrasonic energy to a packed column is covered in United States Patent 2,265,762 filed by Donald S. McKittrich and Robert E. Cornish of Shell Development Company, San Francisco. In the Example section of the patent they use an insulated column equipped with a spiral wire helix and an electric automobile horn attached to a right-angle extension of the column. The results show an increase of 55% in the number of theoretical plates in the column over what was observed without sound. The claims they made are quoted:(20)

> 1. In a distillation process wherein ascending vapors contact liquid reflux in a reflux zone, the step of subjecting the overhead vapors in said zone to the influence of sonic vibration of frequencies between 50 cycles per second and 5 megacycles per second, thereby increasing efficiency of fractionation and reducing the necessary number of theoretical plates.
>
> 2. The process of claim 1 wherein the sonic vibrations have such frequencies as to be in resonance with the natural frequencies of said reflux zone.

The patent discusses several other methods of sonic excitement including the use of several points of introduction of sonic vibrations, the method employed in the experimental section of this thesis.

There have been many other experiments performed with the aid of a sonic vibrations(21)-(26) but none to the author's knowledge use transducers affixed to the surface of a packed column to excite the packing as well as the two process phases.

## 5. Object of Research

The object of this research is to investigate the possibility of using ultrasonic vibration to improve the separation of a packed column operating at total reflux.

## EXPERIMENTAL APPARATUS

The experimental apparatus is shown schematically in Figure 2. A Pyrex column 2.0 inches ID and 40.0 inches long is packed to 36.0 inches with 0.25 inch ceramic berl saddles. The packing is supported by a perforated Teflon support plant having 55, 0.1875 inch holes on a 0.375 inch triangular pitch. Two Kimax heads are identical having 0.50 inch center nozzles and 0.75 inch side nozzles.

The overhead condenser, 18.0 inches long, provides approximately bubble-point reflux through the reflux return pipe. The gas sample outlet has a dual purpose; during normal operation the overhead temperature is monitored by a thermometer inserted in the nozzle through a flexible Neoprene coupling while during sampling operations a glass tube connected to a flash immersed in an ice bath is inserted through the coupling to condense an overhead vapor sample.

The necessary vapor is provided to the column by a reboiler consisting of a 2,000 ml two neck flash equipped with a hemispherical mantle and Powerstat. Tygon tubing and glass fittings connect the reboiler to the reboiler head. The reboiler temperature can be observed on a thermometer inserted in the oil well of the reboiler while the bottoms liquid can be removed through the liquid sample outlet.

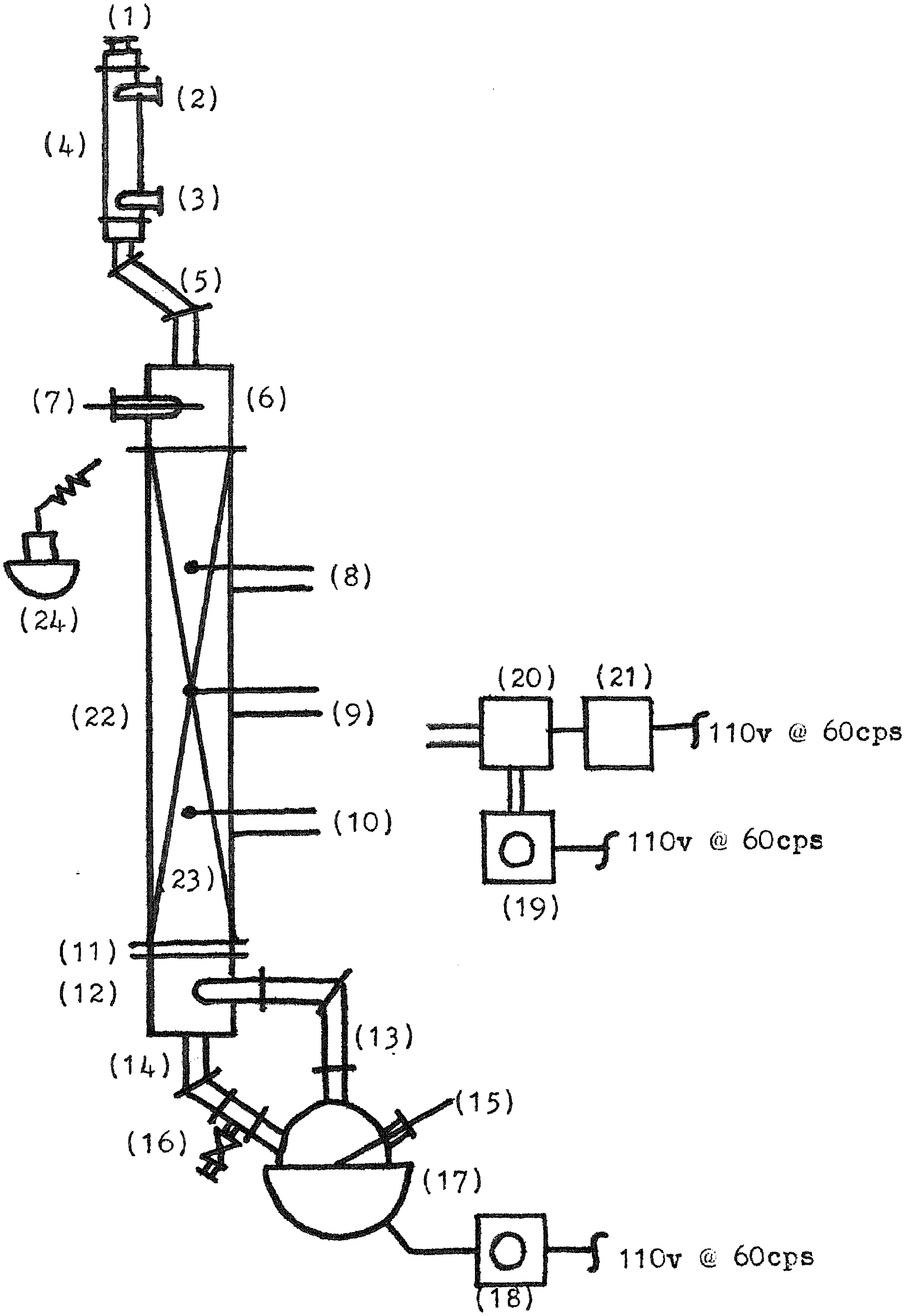


Figure 5. Schematic Digram of Experimental Appaɍatus

## Table 1. Key to Figure 5.

| Notation | Description |
|---|---|
| (1) | Atmospheric vent |
| (2) | Cooling water outlet |
| (3) | Cooling water inlet |
| (4) | Overhead reflux condenser |
| (5) | Reflux return pipe |
| (6) | Reflux head |
| (7) | Gas sample outlet (thermometer inserted) |
| (8) | Leads to top transducers |
| (9) | Leads to middle transducers |
| (10) | Leads to bottom transducers |
| (11) | Packing support plate |
| (12) | Reboiler head |
| (13) | Vapor return pipe |
| (14) | Liquid return pipe |
| (15) | Reboiler with thermometer well |
| (16) | Liquid sample outlet valve |
| (17) | Hemispherical heating mantle |
| (18) | Powerstat type 116 |
| (19) | RCA WA-44C Sine/Square Wave Audio Generator |
| (20) | McIntosh No. 50-W-2 Amplifier |
| (21) | McIntosh NO. P-50-D Power Supply |
| (22) | Pyrex column |
| (23) | Ceramic packing |
| (24) | Vapor ice trap |

Three pairs of Gulton 2D3-53G lead zirconate titanate transducers are epoxyed to the column 9, 18, and 27 inches from the packing support plate and oriented 180° apart. Each pair is wired in series with a McIntosh Model 50-W-2 Amplifier and Power Supply driven by an RCA Model 44 Sine/Square Audio Generator.

## Table 3. Summary of 2D3 G-53 Specifications

| Specification | Quantity |
|---|---|
| Material | Lead zirconate titanate |
| Diameter | 0.25 inch |
| Thickness | 0.05 inch |
| Free dielectric constant | |
| $K_3$ | 720 |
| $K_1$ | 960 |
| Loss tan | 0.022 |
| Normal density | 7.6 $gm/cm^3$ |
| Curie temperature | 330°C |
| Coupling coefficients | |
| $k_{33}$ | 0.60 |
| $k_p$ | 0.50 |
| $k_{31}$ | 0.29 |
| $k_{15}$ | 0.64 |
| Piezoelectric charge coefficient | |
| $d_{33}$ | $190*10^{-12}$ meters/volt |
| $d_{31}$ | $-84*10^{-12}$ meters/volt |
| $d_{15}$ | $300*10^{-12}$ meters/volt |
| Piezoelectric voltage coefficient | |
| $g_{33}$ | $30*10^{-3}$ volt-meter/Newton |
| $g_{31}$ | $-13*10^{-3}$ volt-meter/Newton |
| $g_{15}$ | $36*10^{-3}$ volt-meter/Newton |

Table 3. - continued

| Specification | Quantity |
|---|---|
| Elastic modulus | |
| $Y_{33}$ | $6.5*10^{10}$ Newtons/meters$^2$ |
| $Y_{11}$ | $8.1*10^{10}$ Newtons/meters$^2$ |
| $Y_{55}$ | $3.8*10^{10}$ Newtons/meters$^2$ |
| Mechanical quality factor | 140 |
| Coercive field | 13 Kv/cm @ 60 cycles |
| Remanent polarization | 26 microcoulombs/cm$^2$ |

## EXPERIMENTAL PROCEDURE

### 1. Determination of Operating Conditions

Because the heats of vaporization for the components vary (refer to Table 2), it is necessary to obtain operating conditions for each system. Once these conditions are set they remain constant while the particular system is under consideration.

a. The reboiler is charged with 1000 ml of a 50-50 volumetric mixture of the system and the Powerstat is set at 100.

b. As vigorous boiling occurs, the overhead condenser is partially commissioned and the vent is opened to pressure relieve the column.

c. As the condensing vapors become visible in the overhead condenser, the condenser is fully commissioned.

d. The system is now observed for a period of 30 minutes and the powerstat setting and cooling water rate are adjusted to achieve stable operation and approximately bubble point reflux. The reflux conditions can be observed by sliding the thermometer in the gas sample outlet in and out observing the temperature of the ascending vapors and returning reflux. Because no overhead product is being taken the vapor and liquid will have the same composition and the bubble point and dew point temperature will be identical.

e. Once satisfactory conditions are reached the Powerstat setting, reboiler temperature, and overhead vapor temperature are recorded.

f. A glass tube connected by a piece of flexible Tygon tubing to a flask immersed in an ice bath is inserted into the gas sample outlet to obtain a sample of the ascending vapor.

g. The liquid sample outlet is opened and after draining the residual liquid a sample of the bottoms liquid is obtained.

h. The unused sample of the condensed overhead vapor and bottoms liquid is combined with the residual liquid drained from the liquid sample outlet and introduced back into the column through the vent.

### 2. Ultrasonic Operation

The operating conditions for each system are established in Part 1 and will remain constant for the duration of experimentation made on each system.

a. A frequency of 20 Kcps is set on the sine/square wave audio generator and the column is allowed approximately 15 minutes to come to steady-state.

This steady state condition is determined by the fluctuation in the overhead vapor temperature.

b. Repeat steps e. through h. of Part 1.

c. Increment the frequency 5 Kcps and repeat steps b. and c. of Part 2 until samples are taken at 100 Kcps.

3. Changing Systems

After the experimentation on a given system was completed the column was cleaned by refluxing 500 ml of acetone for 30 minutes at which time the reflux head was removed without disturbing the packing and the acetone was allowed to evaporate for at least 8 hours. The reboiler is then charged with 500 ml of the next system and again the system is operated under total reflux for 1 hour, then allowed to cool. The reboiler is drained and charged as in Part 1. a. and experimentation is begun.

# SYSTEM VARIABLES

## 1. Selection of Systems

The seven systems used in this thesis were chosen because they consist of common chemicals whose normal boiling points are 100°C or less. They were paired to give the maximum difference in refractive index so this property could be used to measure their composition without the use of elaborate sampling techniques such as gas chromatography. A sample of only three or four drops is needed to determine the composition within the four place accuracy of the refractometer. This sample when compared to the 1,000 ml charge has a negligible effect on the liquid and vapor loadings in the column, thus eliminating the necessity of taking simultaneous overhead and bottoms samples. The pairings used were also chosen to give maximum and minimum boiling azeotropic binary mixtures as well as full range composition mixtures so the effect of ultrasonic operation would cover all possible combinations.

## 2. Determination of Experimental Data

Before any experimentation could begin it was necessary to determine the refractive indices of the various systems over the entire composition range. This was accomplished by determining the refractive indices of precisely measured samples of each system. It was found that the refractive index of these mixtures was, within experimental error, a linear function of the mole percent of one of the components.

The mole percent was calculated from the given volume percent, the molecular weight and the specific gravity by assuming perfect mixing. Because only a comparative approach to the ultrasonic operations is under investigation here, this method of determining composition is sufficient.

### 3. Limits of Ultrasonic Operation

The power relationship used in the evaluations were developed for frequencies well below the resonant frequency, so an upper limit of 100 Kcps was set which is consistent with the response curve of the amplifier which is relatively flat between 20 Kcps and 100 Kcps.

## Table 2. Physical Properties of the Components

| Component | Normal Boiling Point, °C | Molecular Weight | Specific Gravity $gm/cm^3$ | Refractive Index |
|---|---|---|---|---|
| Acetone | 56.5 | 58.08 | 0.7899 | 1.3543 |
| Benzene | 80.1 | 78.12 | 0.8787 | 1.4949 |
| Carbon Tetrachloride | 76.7 | 153.82 | 1.5940 | 1.4548 |
| Chloroform | 61.3 | 119.38 | 1.4832 | 1.4402 |
| Ethanol | 78.4 | 46.07 | 0.7893 | 1.3574 |
| Ethylacetate | 77.1 | 88.12 | 0.9003 | 1.3676 |
| Water | 100.0 | 18.06 | 0.9966 | 1.3314 |

Table 2. Physical Properties of the Components - Cont'd

| | Heat of Vaporization | | |
|---|---|---|---|
| Component | cal/gm mol | cal/gm | $cal/cm^3$ |
| Acetone | 7642 | 131.6 | 103.9 |
| Benzene | 8147 | 104.3 | 91.6 |
| Carbon Tetrachloride | 8272 | 53.8 | 85.7 |
| Chloroform | 7501 | 62.8 | 93.2 |
| Ethanol | 9674 | 210.0 | 165.7 |
| Ethylacetate | 8301 | 94.2 | 84.8 |
| Water | 7416 | 410.6 | 409.2 |

## Table 4. Steady State Conditions Experimental Data

| Mixture | $T_o$ | $R_o$ | $Y_A$ | $T_b$ | $R_b$ | $X_A$ | P |
|---|---|---|---|---|---|---|---|
| Benzene (A) - Ethanol (B) | 65.7 | 1.4206 | 45.96 | 70.6 | 1.4094 | 37.81 | 100 |
| Carbon Tetrachloride (A) - Ethanol (B) | 61.4 | 1.4076 | 51.54 | 65.1 | 1.3907 | 34.19 | 105 |
| Carbon Tetrachloride (A) - Ethylacetate (B) | 72.1 | 1.3980 | 34.86 | 74.1 | 1.4165 | 56.08 | 90 |
| Chloroform (A) - Acetone (B) | 60.3 | 1.4105 | 65.42 | 61.1 | 1.3939 | 46.09 | 85 |
| Chloroform (A) - Benzene (B) | 67.4 | 1.4535 | 75.69 | 77.5 | 1.4696 | 46.26 | 90 |
| Chloroform (A) - Ethanol (B) | 58.2 | 1.4123 | 66.31 | 61.6 | 1.3865 | 35.15 | 100 |
| Ethanol (A) - Water (B) | 76.2 | 1.3507 | 74.23 | 87.4 | 1.3335 | 8.07 | 85 |

## DESCRIPTION OF ULTRASONIC OPERATIONS

### 1. Benzene (A) - Ethanol (B) Mixture

In normal distillation processes the pressure and temperature increase from the top to the bottom of the column. This would mean once the azeotropic composition had been reached the conditions in the column due to the pressure and temperature profiles would work against any improvement in separation.

As can be seen in this system, which is a minimum boiling azeotropic binary mixture, the overhead composition reached the azeotropic composition and remained relatively constant. To improve the separation beyond the atmospheric azeotropic composition, the column would have to be operated under vacuum which would mean greater initial and operating costs.

### 2. Carbon Tetrachloride (A) - Ethanol (B) Mixture

This is also a minimum boiling azeotropic binary mixture which is limited by the conditions mentioned in the previous section; however, other difficulties were encountered while dealing with this system.

Violent oscillation was encountered during the operation of this system. While driving the two top transducers above 65 Kcps slugs of liquid were noticed being carried by the vapor into the overhead condenser causing a momentary dry point followed by flooding in the upper section of the column. While driving the two middle transducers above 75 Kcps, there were short durations of no overhead vapor followed by no bottoms liquid which indicates reverse flow occuring in the mid-section of the column. When the two bottom transducers were driven above 90 Kcps, the reboiler started to pulsate, sending slugs of liquid into the reboiler head; this condition was alleviated by pinching down on the liquid return pipe (Tygon tubing).

The aforementioned upsets in the ultrasonic operation of the column caused the termination of experimentation on these systems at the respective frequencies.

### 3. Carbon Tetrachloride (A) - Ethylacetate (B) Mixture

This system is a minimum boiling azeotropic binary mixture which performed similar to the Benzene (A) - Ethanol (B) mixture. No difficulties were encountered during the experimentation on this system.

### 4. Chloroform (A) - Acetone (B) Mixture

This was the only maximum boiling azeotropic binary mixture investigated. Because the normal operating conditions of a distillation column (decreasing temperature from bottom to top) favors continued separation once the azeotropic composition has been reached, it was expected that the overhead composition would readily pass the atmospheric azeotropic composition.

As can be seen in Figure 9., the azeotropic composition (Separation Factor = 1.000) was passed at a fairly low frequency and from the slope of the curve continued improvement could be expected as the frequency is increased.

### 5. Chloroform (A) - Benzene (B) Mixture

This is the only full range binary mixture used for experimentation. As in the previous systems, the separation factor increases with increasing frequency; however, unlike the previous systems a maximum is reached at which point there is a decrease in the separation factor. Because this condition was experienced only with this system, the components rather than the packing must begin to resonate at some characteristic frequency causing a decrease in the efficiency of contacting.

### 6. Chloroform (A) - Ethanol (B) Mixture

Because this system is a minimum boiling azeotropic binary mixture, it was expected the system would perform similarly to the previous systems, but this was not the case.

When the separation factor reached approximately 0.950 (95% of the azeotropic composition), a foaming mixture appeared on the top of the packing. As the frequency was increased, the foam totally filled the reflux head causing the investigation of this system to be terminated.

When the two bottom transducers were driven above 60 Kcps, there was no improvement in the overhead composition. This combined with the previous evidence of foam indicates the presence of foam in the center section of the packing.

## 7. Ethanol (A) - Water (B) Mixture

Because of previous experience with the ethanol - water mixture it was expected that difficulties would be encountered during operations. Because the 50-50 volumetric mixture is only 23.54 mole percent ethanol, a quasi-steam distillation effect governs this system during certain operations. As can be seen from Figure 12, when driving the two top transducers, the atmospheric azeotropic composition was easily passed and compositions in the 96%-plus range were experienced. Only small amounts of overhead vapor were noted indicating the reflux was vaporizing as soon as it came in contact with the upper surface of the packing. The bottoms liquid was 90%-plus water, reinforcing the theory that steam was supplying heat to the packing without contacting any descending liquid.

Table 5. Benzene(A)-Ethanol(B) Mixture

| Volume Percent(A) | Mole Percent(A) | Refractive Index |
|---|---|---|
| 0 | 0.00 | 1.3574 |
| 5 | 3.35 | 1.3620 |
| 10 | 6.81 | 1.3668 |
| 15 | 10.40 | 1.3727 |
| 20 | 14.12 | 1.3768 |
| 25 | 17.99 | 1.3821 |
| 30 | 21.99 | 1.3876 |
| 35 | 26.16 | 1.3934 |
| 40 | 30.49 | 1.3993 |
| 45 | 34.99 | 1.4055 |
| 50 | 39.68 | 1.4120 |
| 55 | 44.57 | 1.4187 |
| 60 | 49.67 | 1.4257 |
| 65 | 54.99 | 1.4330 |
| 70 | 60.55 | 1.4407 |
| 75 | 66.28 | 1.4485 |
| 80 | 72.41 | 1.4570 |
| 85 | 78.85 | 1.4658 |
| 90 | 85.55 | 1.4750 |
| 95 | 92.59 | 1.4847 |
| 100 | 100.00 | 1.4949 |

| Mole Percent(A) | | |
|---|---|---|
| Liquid | Vapor | Temperature,°C |
| 0 | 0 | 78.1 |
| 6 | 20 | 74.4 |
| 11 | 30 | 72.4 |
| 20 | 40 | 70.1 |
| 39 | 50 | 68.3 |
| 57 | 56 | 67.8 |
| 72 | 60 | 68.3 |
| 89 | 70 | 70.3 |
| 96 | 85 | 75.2 |
| 100 | 100 | 79.7 |

Minimum boiling point azeotropic binary mixture at 55.4 mole percent(A) and 67.9°C.

Mole Percent(A) = (727.27)*(Refractive Index) - 987.20

## Table 6. Benzene (A)-Ethanol (B) Mixture Experimental Data

| Position | Bottom | | | | Middle | | | |
|---|---|---|---|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 65.7 | 70.6 | 1.4206 | 1.4094 | 65.7 | 70.6 | 1.4206 | 1.4094 |
| 25 Kcps | 65.7 | 70.6 | 1.4206 | 1.4094 | 65.7 | 70.6 | 1.4226 | 1.4094 |
| 30 Kcps | 65.7 | 70.6 | 1.4225 | 1.4094 | 65.7 | 70.6 | 1.4232 | 1.4094 |
| 35 Kcps | 65.7 | 70.6 | 1.4231 | 1.4094 | 65.8 | 70.6 | 1.4243 | 1.4094 |
| 40 Kcps | 65.9 | 70.6 | 1.4243 | 1.4094 | 65.8 | 70.6 | 1.4254 | 1.4094 |
| 45 Kcps | 65.9 | 70.6 | 1.4252 | 1.4094 | 65.8 | 70.6 | 1.4259 | 1.4093 |
| 50 Kcps | 65.9 | 70.6 | 1.4258 | 1.4093 | 65.8 | 70.6 | 1.4265 | 1.4093 |
| 55 Kcps | 65.9 | 70.6 | 1.4266 | 1.4093 | 66.0 | 70.6 | 1.4276 | 1.4093 |
| 60 Kcps | 66.1 | 70.6 | 1.4275 | 1.4093 | 66.0 | 70.6 | 1.4286 | 1.4093 |
| 65 Kcps | 66.1 | 70.6 | 1.4284 | 1.4093 | 66.0 | 70.6 | 1.4292 | 1.4094 |
| 70 Kcps | 66.1 | 70.6 | 1.4291 | 1.4093 | 66.4 | 70.6 | 1.4299 | 1.4094 |
| 75 Kcps | 66.4 | 70.6 | 1.4299 | 1.4094 | 66.5 | 70.6 | 1.4311 | 1.4094 |
| 80 Kcps | 66.4 | 70.6 | 1.4309 | 1.4094 | 66.6 | 70.6 | 1.4319 | 1.4094 |
| 85 Kcps | 66.6 | 70.6 | 1.4317 | 1.4094 | 66.6 | 70.6 | 1.4326 | 1.4093 |
| 90 Kcps | 66.6 | 70.6 | 1.4323 | 1.4094 | 66.7 | 70.6 | 1.4333 | 1.4093 |
| 95 Kcps | 66.6 | 70.6 | 1.4330 | 1.4093 | 66.8 | 70.6 | 1.4335 | 1.4093 |
| 100 Kcps | 66.8 | 70.6 | 1.4335 | 1.4093 | 66.8 | 70.6 | 1.4336 | 1.4093 |

Table 6. Benzene (A)-Ethanol (B) Mixture Experimental Data

| Position | Top | | | |
|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 65.7 | 70.6 | 1.4207 | 1.4094 |
| 25 Kcps | 65.7 | 70.6 | 1.4228 | 1.4094 |
| 30 Kcps | 65.8 | 70.6 | 1.4239 | 1.4094 |
| 35 Kcps | 65.8 | 70.6 | 1.4251 | 1.4094 |
| 40 Kcps | 65.9 | 70.6 | 1.4259 | 1.4093 |
| 45 Kcps | 65.9 | 70.6 | 1.4264 | 1.4093 |
| 50 Kcps | 66.0 | 70.6 | 1.4277 | 1.4093 |
| 55 Kcps | 66.1 | 70.6 | 1.4286 | 1.4093 |
| 60 Kcps | 66.3 | 70.6 | 1.4291 | 1.4093 |
| 65 Kcps | 66.4 | 70.6 | 1.4298 | 1.4094 |
| 70 Kcps | 66.5 | 70.6 | 1.4310 | 1.4094 |
| 75 Kcps | 66.6 | 70.6 | 1.4320 | 1.4094 |
| 80 Kcps | 66.6 | 70.6 | 1.4325 | 1.4093 |
| 85 Kcps | 66.7 | 70.6 | 1.4334 | 1.4093 |
| 90 Kcps | 66.8 | 70.6 | 1.4336 | 1.4093 |
| 95 Kcps | 66.8 | 70.6 | 1.4337 | 1.4093 |
| 100 Kcps | 66.8 | 70.6 | 1.4338 | 1.4093 |

## Table 7. Benzene(A)-Ethanol(B) Mixture Separation Factors

| Position | Bottom | | | Middle | | | Top | | |
|---|---|---|---|---|---|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ | $Y_A$ | $F_A$ | $X_A$ | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 45.96 | 0.830 | 37.81 | 45.96 | 0.830 | 37.81 | 46.03 | 0.830 | 37.81 |
| 25 Kcps | 45.96 | 0.830 | 37.81 | 47.41 | 0.856 | 37.81 | 47.56 | 0.858 | 37.81 |
| 30 Kcps | 47.34 | 0.855 | 37.81 | 47.85 | 0.864 | 37.81 | 48.36 | 0.873 | 37.81 |
| 35 Kcps | 47.78 | 0.862 | 37.81 | 48.65 | 0.878 | 37.81 | 49.23 | 0.889 | 37.81 |
| 40 Kcps | 48.65 | 0.878 | 37.81 | 49.45 | 0.893 | 37.81 | 49.81 | 0.899 | 37.74 |
| 45 Kcps | 49.31 | 0.890 | 37.81 | 49.81 | 0.899 | 37.74 | 50.18 | 0.906 | 37.74 |
| 50 Kcps | 49.74 | 0.898 | 37.74 | 50.25 | 0.907 | 37.74 | 51.12 | 0.923 | 37.74 |
| 55 Kcps | 50.32 | 0.908 | 37.74 | 51.05 | 0.921 | 37.74 | 51.78 | 0.935 | 37.74 |
| 60 Kcps | 50.98 | 0.920 | 37.74 | 51.78 | 0.935 | 37.74 | 52.14 | 0.941 | 37.81 |
| 65 Kcps | 51.63 | 0.932 | 37.74 | 52.21 | 0.942 | 37.81 | 52.65 | 0.950 | 37.81 |
| 70 Kcps | 52.14 | 0.941 | 37.74 | 52.72 | 0.952 | 37.81 | 53.52 | 0.966 | 37.81 |
| 75 Kcps | 52.72 | 0.952 | 37.81 | 53.60 | 0.967 | 37.81 | 54.26 | 0.979 | 37.81 |
| 80 Kcps | 53.45 | 0.965 | 37.81 | 54.18 | 0.978 | 37.81 | 54.61 | 0.986 | 37.74 |
| 85 Kcps | 54.03 | 0.975 | 37.81 | 54.69 | 0.987 | 37.74 | 55.27 | 0.998 | 37.74 |
| 90 Kcps | 54.47 | 0.983 | 37.81 | 55.20 | 0.996 | 37.74 | 55.41 | 1.000 | 37.74 |
| 95 Kcps | 54.98 | 0.992 | 37.74 | 55.34 | 0.998 | 37.74 | 55.49 | 1.002 | 37.74 |
| 100 Kcps | 55.34 | 0.998 | 37.74 | 55.41 | 1.000 | 37.74 | 55.56 | 1.003 | 37.74 |

Table 8. Carbon Tetrachloride(A)-Ethanol(B) Mixture

| Volume Percent(A) | Mole Percent(A) | Refractive Index |
|---|---|---|
| 0 | 0.00 | 1.3574 |
| 5 | 3.10 | 1.3604 |
| 10 | 6.32 | 1.3636 |
| 15 | 9.69 | 1.3639 |
| 20 | 13.20 | 1.3703 |
| 25 | 16.86 | 1.3738 |
| 30 | 20.66 | 1.3775 |
| 35 | 24.67 | 1.3814 |
| 40 | 28.85 | 1.3855 |
| 45 | 33.23 | 1.3898 |
| 50 | 37.81 | 1.3942 |
| 55 | 42.64 | 1.3989 |
| 60 | 47.71 | 1.4039 |
| 65 | 53.04 | 1.4091 |
| 70 | 58.66 | 1.4145 |
| 75 | 64.60 | 1.4203 |
| 80 | 70.87 | 1.4264 |
| 85 | 77.51 | 1.4329 |
| 90 | 84.55 | 1.4398 |
| 95 | 92.04 | 1.4470 |
| 100 | 100.00 | 1.4548 |

| Mole Percent(A) | | | |
|---|---|---|---|
| Vapor | Liquid | Temperature,°C | |
| 0 | 0.0 | 77.9 | |
| 25 | 6.4 | 72.8 | |
| 35 | 11.4 | 70.3 | |
| 45 | 17.6 | 68.0 | |
| 55 | 33.6 | 65.0 | Data at 745 mm Hg |
| 60 | 60.0 | 63.8 | |
| 67 | 72.8 | 64.3 | |
| 100 | 100.0 | 75.9 | |

Minimum boiling point azeotropic binary mixture at 61.3 mole percent(A) and 64.95°C.

Mole Percent(A) = (1026.69)*(Refractive Index) - 1393.63

Table 9. Carbon Tetrachloride (A)-Ethanol (B) Mixture Experimental Data

| Position | Top | | | | Middle | | | |
|---|---|---|---|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 61.4 | 65.1 | 1.4076 | 1.3907 | 61.4 | 65.1 | 1.4076 | 1.3907 |
| 25 Kcps | 61.4 | 65.1 | 1.4080 | 1.3907 | 61.4 | 65.1 | 1.4082 | 1.3907 |
| 30 Kcps | 61.4 | 65.1 | 1.4082 | 1.3907 | 61.4 | 65.1 | 1.4090 | 1.3907 |
| 35 Kcps | 61.4 | 65.1 | 1.4088 | 1.3907 | 61.4 | 65.1 | 1.4099 | 1.3908 |
| 40 Kcps | 61.4 | 65.1 | 1.4091 | 1.3907 | 61.4 | 65.1 | 1.4106 | 1.3908 |
| 45 Kcps | 61.4 | 65.1 | 1.4098 | 1.3908 | 61.4 | 65.1 | 1.4114 | 1.3908 |
| 50 Kcps | 61.4 | 65.1 | 1.4102 | 1.3908 | 61.5 | 65.1 | 1.4122 | 1.3908 |
| 55 Kcps | 61.4 | 65.1 | 1.4109 | 1.3908 | 61.6 | 65.1 | 1.4129 | 1.3907 |
| 60 Kcps | 61.4 | 65.1 | 1.4115 | 1.3908 | 61.5 | 65.1 | 1.4136 | 1.3907 |
| 65 Kcps | 61.5 | 65.1 | 1.4121 | 1.3907 | 61.6 | 65.1 | 1.4143 | 1.3907 |
| 70 Kcps | 61.5 | 65.1 | 1.4127 | 1.3907 | 61.6 | 65.1 | 1.4149 | 1.3906 |
| 75 Kcps | 61.5 | 65.1 | 1.4134 | 1.3907 | 61.7 | 65.1 | 1.4154 | 1.3906 |
| 80 Kcps | 61.6 | 65.1 | 1.4140 | 1.3906 | ---- | ---- | ------ | ------ |
| 85 Kcps | 61.6 | 65.1 | 1.4147 | 1.3906 | ---- | ---- | ------ | ------ |
| 90 Kcps | 61.7 | 65.1 | 1.4154 | 1.3906 | ---- | ---- | ------ | ------ |
| 95 Kcps | ---- | ---- | ------ | ------ | ---- | ---- | ------ | ------ |
| 100 Kcps | ---- | ---- | ------ | ------ | ---- | ---- | ------ | ------ |

Table 9. Carbon Tetrachloride (A)-Ethanol (B) Mixture Experimental Data

| Position | Bottom | | | |
|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 61.4 | 65.1 | 1.4076 | 1.3907 |
| 25 Kcps | 61.4 | 65.1 | 1.4088 | 1.3907 |
| 30 Kcps | 61.4 | 65.1 | 1.4101 | 1.3908 |
| 35 Kcps | 61.4 | 65.1 | 1.4114 | 1.3908 |
| 40 Kcps | 61.5 | 65.1 | 1.4124 | 1.3908 |
| 45 Kcps | 61.5 | 65.1 | 1.4134 | 1.3908 |
| 50 Kcps | 61.6 | 65.1 | 1.4142 | 1.3908 |
| 55 Kcps | 61.6 | 65.1 | 1.4150 | 1.3909 |
| 60 Kcps | 61.7 | 65.1 | 1.4154 | 1.3909 |
| 65 Kcps | ---- | ---- | ------ | ------ |
| 70 Kcps | ---- | ---- | ------ | ------ |
| 75 Kcps | ---- | ---- | ------ | ------ |
| 80 Kcps | ---- | ---- | ------ | ------ |
| 85 Kcps | ---- | ---- | ------ | ------ |
| 90 Kcps | ---- | ---- | ------ | ------ |
| 95 Kcps | ---- | ---- | ------ | ------ |
| 100 Kcps | ---- | ---- | ------ | ------ |

## Table 10. Carbon Tetrachloride (A)-Ethanol (B) Mixture Separation Factors

| Position | | | | | | |
|---|---|---|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 51.54 | 0.841 | 34.19 | 51.54 | 0.841 | 34.19 |
| 25 Kcps | 51.95 | 0.847 | 34.19 | 52.15 | 0.851 | 34.19 |
| 30 Kcps | 52.15 | 0.851 | 34.19 | 52.98 | 0.864 | 34.19 |
| 35 Kcps | 52.77 | 0.861 | 34.19 | 53.90 | 0.879 | 34.29 |
| 40 Kcps | 53.08 | 0.866 | 34.19 | 54.62 | 0.891 | 34.29 |
| 45 Kcps | 53.80 | 0.877 | 34.29 | 55.44 | 0.904 | 34.29 |
| 50 Kcps | 54.21 | 0.884 | 34.29 | 56.26 | 0.918 | 34.29 |
| 55 Kcps | 54.93 | 0.896 | 34.20 | 56.98 | 0.930 | 34.19 |
| 60 Kcps | 55.54 | 0.906 | 34.29 | 57.70 | 0.941 | 34.19 |
| 65 Kcps | 56.16 | 0.916 | 34.19 | 58.42 | 0.953 | 34.19 |
| 70 Kcps | 56.77 | 0.926 | 34.19 | 59.03 | 0.963 | 34.09 |
| 75 Kcps | 57.49 | 0.938 | 34.19 | 59.55 | 0.971 | 34.09 |
| 80 Kcps | 58.11 | 0.948 | 34.09 | ------ | ------ | ----- |
| 85 Kcps | 58.83 | 0.960 | 34.09 | ------ | ------ | ----- |
| 90 Kcps | 59.55 | 0.971 | 34.09 | ------ | ------ | ----- |
| 95 Kcps | ----- | ----- | ------ | ------ | ------ | ----- |
| 100 Kcps | ----- | ----- | ------ | ------ | ------ | ----- |

Table 10. Carbon Tetrachloride (A)-Ethanol (B) Mixture Separation Factors

| Position<br>Frequency | $Y_A$ | $F_A$ | $X_A$ |
|---|---|---|---|
| 20 Kcps | 51.54 | 0.841 | 34.19 |
| 25 Kcps | 52.77 | 0.861 | 34.19 |
| 30 Kcps | 54.11 | 0.883 | 34.29 |
| 35 Kcps | 55.44 | 0.904 | 34.29 |
| 40 Kcps | 56.47 | 0.921 | 34.29 |
| 45 Kcps | 57.49 | 0.938 | 34.29 |
| 50 Kcps | 58.31 | 0.951 | 34.29 |
| 55 Kcps | 59.14 | 0.965 | 34.39 |
| 60 Kcps | 59.55 | 0.971 | 34.39 |
| 65 Kcps | ----- | ----- | ----- |
| 70 Kcps | ----- | ----- | ----- |
| 75 Kcps | ----- | ----- | ----- |
| 80 Kcps | ----- | ----- | ----- |
| 85 Kcps | ----- | ----- | ----- |
| 90 Kcps | ----- | ----- | ----- |
| 95 Kcps | ----- | ----- | ----- |
| 100 Kcps | ----- | ----- | ----- |

Table 11. Carbon Tetrachloride(A)-Ethylacetate(B) Mixture

| Volume Percent(A) | Mole Percent(A) | Refractive Index |
|---|---|---|
| 0 | 0.00 | 1.3676 |
| 5 | 5.09 | 1.3720 |
| 10 | 10.18 | 1.3765 |
| 15 | 15.25 | 1.3809 |
| 20 | 20.31 | 1.3853 |
| 25 | 25.37 | 1.3897 |
| 30 | 30.41 | 1.3941 |
| 35 | 35.44 | 1.3981 |
| 40 | 40.46 | 1.4029 |
| 45 | 45.48 | 1.4073 |
| 50 | 50.49 | 1.4116 |
| 55 | 55.48 | 1.4160 |
| 60 | 60.46 | 1.4203 |
| 65 | 65.44 | 1.4247 |
| 70 | 70.41 | 1.4290 |
| 75 | 75.36 | 1.4333 |
| 80 | 80.31 | 1.4376 |
| 85 | 85.24 | 1.4419 |
| 90 | 90.17 | 1.4462 |
| 95 | 95.09 | 1.4505 |
| 100 | 100.00 | 1.4548 |

| Mole Percent(A) | | | |
|---|---|---|---|
| Vapor | Liquid | Temperature,°C | |
| 0 | 0.0 | 76.5 | |
| 10 | 9.5 | 75.8 | |
| 20 | 17.9 | 75.2 | |
| 30 | 28.4 | 74.7 | Data at 745 mm Hg |
| 40 | 37.3 | 74.3 | |
| 50 | 44.0 | 74.1 | |
| 60 | 58.0 | 74.1 | |
| 70 | 68.2 | 74.3 | |
| 85 | 83.9 | 74.9 | |
| 100 | 100.0 | 75.9 | |

Minimum boiling point azeotropic binary mixture at 43.0 mole percent(A) and 74.75°C.

Mole Percent(A) = (1146.79)*(Refractive Index) - 1568.35

Table 12. Carbon Tetrachloride (A)-Ethylacetate (B) Mixture Experimental Data

| Position | Bottom | | | | Middle | | | |
|---|---|---|---|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 72.1 | 74.1 | 1.3980 | 1.4165 | 72.1 | 74.1 | 1.3980 | 1.4165 |
| 25 Kcps | 72.1 | 74.1 | 1.3989 | 1.4165 | 72.1 | 74.1 | 1.3995 | 1.4165 |
| 30 Kcps | 72.1 | 74.1 | 1.3995 | 1.4165 | 72.1 | 74.1 | 1.4004 | 1.4165 |
| 35 Kcps | 72.1 | 74.1 | 1.4001 | 1.4165 | 72.1 | 74.1 | 1.4013 | 1.4165 |
| 40 Kcps | 72.1 | 74.1 | 1.4006 | 1.4165 | 72.1 | 74.1 | 1.4020 | 1.4165 |
| 45 Kcps | 72.1 | 74.1 | 1.4011 | 1.4165 | 72.1 | 74.1 | 1.4027 | 1.4165 |
| 50 Kcps | 72.1 | 74.1 | 1.4017 | 1.4165 | 72.2 | 74.1 | 1.4032 | 1.4165 |
| 55 Kcps | 72.2 | 74.1 | 1.4023 | 1.4165 | 72.3 | 74.1 | 1.4037 | 1.4166 |
| 60 Kcps | 72.2 | 74.1 | 1.4026 | 1.4165 | 72.3 | 74.1 | 1.4042 | 1.4166 |
| 65 Kcps | 72.2 | 74.1 | 1.4031 | 1.4165 | 72.3 | 74.1 | 1.4045 | 1.4166 |
| 70 Kcps | 72.3 | 74.1 | 1.4035 | 1.4166 | 72.3 | 74.1 | 1.4047 | 1.4166 |
| 75 Kcps | 72.3 | 74.1 | 1.4039 | 1.4166 | 72.3 | 74.1 | 1.4049 | 1.4166 |
| 80 Kcps | 72.3 | 74.1 | 1.4041 | 1.4166 | 72.3 | 74.1 | 1.4051 | 1.4167 |
| 85 Kcps | 72.3 | 74.1 | 1.4045 | 1.4166 | 72.4 | 74.1 | 1.4050 | 1.4167 |
| 90 Kcps | 72.3 | 74.1 | 1.4048 | 1.4166 | 72.4 | 74.1 | 1.4050 | 1.4167 |
| 95 Kcps | 72.3 | 74.1 | 1.4050 | 1.4167 | 72.4 | 74.1 | 1.4050 | 1.4167 |
| 100 Kcps | 72.4 | 74.1 | 1.4051 | 1.4167 | 72.4 | 74.1 | 1.4051 | 1.4167 |

Table 12. Carbon Tetrachloride (A)-Ethylacetate (B) Mixture Experimental Data

| Position Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
|---|---|---|---|---|
| 20 Kcps | 72.1 | 74.1 | 1.3983 | 1.4165 |
| 25 Kcps | 72.1 | 74.1 | 1.4007 | 1.4165 |
| 30 Kcps | 72.1 | 74.1 | 1.4018 | 1.4165 |
| 35 Kcps | 72.2 | 74.1 | 1.4026 | 1.4165 |
| 40 Kcps | 72.2 | 74.1 | 1.4031 | 1.4165 |
| 45 Kcps | 72.3 | 74.1 | 1.4036 | 1.4165 |
| 50 Kcps | 72.3 | 74.1 | 1.4038 | 1.4166 |
| 55 Kcps | 72.3 | 74.1 | 1.4044 | 1.4166 |
| 60 Kcps | 72.3 | 74.1 | 1.4048 | 1.4166 |
| 65 Kcps | 72.3 | 74.1 | 1.4051 | 1.4166 |
| 70 Kcps | 72.3 | 74.1 | 1.4050 | 1.4166 |
| 75 Kcps | 72.4 | 74.1 | 1.4050 | 1.4166 |
| 80 Kcps | 72.4 | 74.1 | 1.4051 | 1.4166 |
| 85 Kcps | 72.4 | 74.1 | 1.4051 | 1.4167 |
| 90 Kcps | 72.4 | 74.1 | 1.4050 | 1.4167 |
| 95 Kcps | 72.4 | 74.1 | 1.4053 | 1.4167 |
| 100 Kcps | 72.4 | 74.1 | 1.4055 | 1.4167 |

Table 13. Carbon Tetrachloride (A)-Ethylacetate (B) Mixture Separation Factor

| Position | Bottom | | | Middle | | |
|---|---|---|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 34.86 | 0.811 | 56.08 | 34.86 | 0.811 | 56.08 |
| 25 Kcps | 35.89 | 0.835 | 56.08 | 36.59 | 0.851 | 56.08 |
| 30 Kcps | 36.58 | 0.851 | 56.08 | 37.61 | 0.875 | 56.08 |
| 35 Kcps | 37.27 | 0.867 | 56.08 | 38.65 | 0.899 | 56.08 |
| 40 Kcps | 37.84 | 0.880 | 56.08 | 39.45 | 0.917 | 56.08 |
| 45 Kcps | 38.42 | 0.893 | 56.08 | 40.25 | 0.936 | 56.08 |
| 50 Kcps | 39.11 | 0.909 | 56.08 | 40.83 | 0.949 | 56.08 |
| 55 Kcps | 39.79 | 0.925 | 56.08 | 41.40 | 0.963 | 56.19 |
| 60 Kcps | 40.14 | 0.933 | 56.08 | 41.97 | 0.976 | 56.19 |
| 65 Kcps | 40.71 | 0.947 | 56.08 | 42.32 | 0.984 | 56.19 |
| 70 Kcps | 41.17 | 0.957 | 56.19 | 42.55 | 0.989 | 56.19 |
| 75 Kcps | 41.63 | 0.968 | 56.19 | 42.78 | 0.995 | 56.19 |
| 80 Kcps | 41.86 | 0.973 | 56.19 | 43.00 | 1.000 | 56.31 |
| 85 Kcps | 42.32 | 0.984 | 56.19 | 42.89 | 0.997 | 56.31 |
| 90 Kcps | 42.66 | 0.992 | 56.19 | 42.89 | 0.997 | 56.31 |
| 95 Kcps | 42.89 | 0.997 | 56.31 | 42.89 | 0.997 | 56.31 |
| 100 Kcps | 43.00 | 1.000 | 56.31 | 43.00 | 1.000 | 56.31 |

Table 13. Carbon Tetrachloride (A)-Ethylacetate (B) Mixture Separation Factor

| Position | | Top | |
|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 35.21 | 0.819 | 56.08 |
| 25 Kcps | 37.94 | 0.882 | 56.08 |
| 30 Kcps | 39.22 | 0.912 | 56.08 |
| 35 Kcps | 40.14 | 0.933 | 56.08 |
| 40 Kcps | 40.71 | 0.947 | 56.08 |
| 45 Kcps | 41.28 | 0.960 | 56.08 |
| 50 Kcps | 41.51 | 0.965 | 56.19 |
| 55 Kcps | 42.20 | 0.981 | 56.19 |
| 60 Kcps | 42.66 | 0.992 | 56.19 |
| 65 Kcps | 43.00 | 1.000 | 56.19 |
| 70 Kcps | 42.89 | 0.997 | 56.19 |
| 75 Kcps | 42.89 | 0.997 | 56.19 |
| 80 Kcps | 43.00 | 1.000 | 56.19 |
| 85 Kcps | 43.00 | 1.000 | 56.31 |
| 90 Kcps | 42.89 | 0.997 | 56.31 |
| 95 Kcps | 42.23 | 1.005 | 56.31 |
| 100 Kcps | 43.46 | 1.001 | 56.31 |

## Table 14. Chloroform(A)-Acetone(B) Mixture

| Volume Percent(A) | Mole Percent(A) | Refractive Index |
|---|---|---|
| 0 | 0.00 | 1.3543 |
| 5 | 4.61 | 1.3583 |
| 10 | 9.27 | 1.3623 |
| 15 | 13.96 | 1.3663 |
| 20 | 18.68 | 1.3704 |
| 25 | 23.45 | 1.3744 |
| 30 | 28.26 | 1.3786 |
| 35 | 33.11 | 1.3827 |
| 40 | 37.99 | 1.3869 |
| 45 | 42.92 | 1.3912 |
| 50 | 47.89 | 1.3954 |
| 55 | 52.90 | 1.3997 |
| 60 | 57.96 | 1.4041 |
| 65 | 63.03 | 1.4084 |
| 70 | 68.20 | 1.4129 |
| 75 | 73.39 | 1.4173 |
| 80 | 78.62 | 1.4218 |
| 85 | 83.89 | 1.4264 |
| 90 | 89.21 | 1.4309 |
| 95 | 94.53 | 1.4352 |
| 100 | 100.00 | 1.4402 |

| Mole Percent(A) | | |
|---|---|---|
| Liquid | Vapor | Temperature, °C |
| 0.00 | 0.00 | 56.2 |
| 8.55 | 4.78 | 57.5 |
| 14.10 | 8.35 | 58.3 |
| 20.45 | 13.12 | 59.4 |
| 26.12 | 17.65 | 60.4 |
| 33.67 | 24.95 | 61.6 |
| 42.50 | 35.20 | 62.8 |
| 52.29 | 48.30 | 63.9 |
| 73.40 | 76.30 | 64.4 |
| 78.92 | 82.40 | 63.8 |
| 86.25 | 90.00 | 63.1 |
| 88.92 | 93.50 | 62.8 |
| 100.00 | 100.00 | 61.3 |

Maximum boiling point azeotropic binary mixture at 65.5 mole percent(A) and 64.5°C.

Mole Percent(A) = (1164.14)*(Refractive Index) - 1576.60

## Table 15. Chloroform(A)-Acetone(B) Mixture Experimental Data

| Position | | Bottom | | | | Middle | | |
|---|---|---|---|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 60.4 | 61.1 | 1.4104 | 1.3939 | 60.3 | 61.1 | 1.4105 | 1.3939 |
| 25 Kcps | 60.4 | 61.1 | 1.4112 | 1.3938 | 60.3 | 61.1 | 1.4115 | 1.3938 |
| 30 Kcps | 60.4 | 61.1 | 1.4120 | 1.3932 | 60.3 | 61.1 | 1.4125 | 1.3933 |
| 35 Kcps | 60.5 | 61.1 | 1.4125 | 1.3930 | 60.4 | 61.1 | 1.4137 | 1.3929 |
| 40 Kcps | 60.6 | 61.1 | 1.4129 | 1.3928 | 60.4 | 61.1 | 1.4148 | 1.3927 |
| 45 Kcps | 60.6 | 61.1 | 1.4135 | 1.3927 | 60.4 | 61.1 | 1.4155 | 1.3925 |
| 50 Kcps | 60.6 | 61.1 | 1.4141 | 1.3926 | 60.4 | 61.1 | 1.4166 | 1.3923 |
| 55 Kcps | 60.6 | 61.1 | 1.4144 | 1.3923 | 60.4 | 61.1 | 1.4169 | 1.3921 |
| 60 Kcps | 60.6 | 61.1 | 1.4146 | 1.3923 | 60.5 | 61.1 | 1.4175 | 1.3920 |
| 65 Kcps | 60.6 | 61.1 | 1.4148 | 1.3922 | 60.6 | 61.1 | 1.4180 | 1.3919 |
| 70 Kcps | 60.6 | 61.1 | 1.4150 | 1.3921 | 60.6 | 61.1 | 1.4186 | 1.3920 |
| 75 Kcps | 60.6 | 61.1 | 1.4152 | 1.3920 | 60.6 | 61.1 | 1.4193 | 1.3920 |
| 80 Kcps | 60.6 | 61.1 | 1.4155 | 1.3919 | 60.6 | 61.1 | 1.4200 | 1.3920 |
| 85 Kcps | 60.6 | 61.1 | 1.4158 | 1.3921 | 60.6 | 61.1 | 1.4210 | 1.3920 |
| 90 Kcps | 60.7 | 61.1 | 1.4164 | 1.3920 | 60.7 | 61.2 | 1.4219 | 1.3920 |
| 95 Kcps | 60.6 | 61.1 | 1.4169 | 1.3920 | 60.6 | 61.2 | 1.4231 | 1.3920 |
| 100 Kcps | 60.6 | 61.1 | 1.4173 | 1.3920 | 60.8 | 61.2 | 1.4241 | 1.3920 |

## Table 15. Chloroform(A)-Acetone(B) Mixture Experimental Data - Cont'd

| Position | | Top | | |
|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 60.5 | 61.1 | 1.4105 | 1.3939 |
| 25 Kcps | 60.5 | 61.1 | 1.4123 | 1.3937 |
| 30 Kcps | 60.5 | 61.1 | 1.4140 | 1.3930 |
| 35 Kcps | 60.6 | 61.1 | 1.4152 | 1.3927 |
| 40 Kcps | 60.6 | 61.1 | 1.4163 | 1.3925 |
| 45 Kcps | 60.8 | 61.1 | 1.4171 | 1.3923 |
| 50 Kcps | 60.8 | 61.2 | 1.4180 | 1.3922 |
| 55 Kcps | 60.8 | 61.1 | 1.4190 | 1.3920 |
| 60 Kcps | 60.8 | 61.1 | 1.4200 | 1.3921 |
| 65 Kcps | 60.9 | 61.1 | 1.4210 | 1.3921 |
| 70 Kcps | 60.8 | 61.1 | 1.4219 | 1.3920 |
| 75 Kcps | 60.9 | 61.2 | 1.4228 | 1.3920 |
| 80 Kcps | 60.9 | 61.2 | 1.4236 | 1.3919 |
| 85 Kcps | 60.9 | 61.2 | 1.4246 | 1.3919 |
| 90 Kcps | 60.9 | 61.2 | 1.4256 | 1.3920 |
| 95 Kcps | 60.9 | 61.2 | 1.4271 | 1.3918 |
| 100 Kcps | 61.0 | 6.14 | 1.4283 | 1.3918 |

## Table 16. Chloroform(A)-Acetone(B) Mixture Separation Factors

| Position | Bottom | | | Middle | | | Top | | |
|---|---|---|---|---|---|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ | $Y_A$ | $F_A$ | $X_A$ | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 63.30 | 0.997 | 46.09 | 65.42 | 0.999 | 46.09 | 65.42 | 0.999 | 46.09 |
| 25 Kcps | 66.23 | 1.011 | 45.98 | 66.58 | 1.017 | 45.98 | 67.51 | 1.031 | 45.86 |
| 30 Kcps | 67.17 | 1.025 | 45.28 | 67.75 | 1.034 | 45.40 | 69.49 | 1.061 | 45.05 |
| 35 Kcps | 67.75 | 1.034 | 45.05 | 69.14 | 1.056 | 44.93 | 70.89 | 1.082 | 44.70 |
| 40 Kcps | 68.21 | 1.041 | 44.81 | 70.43 | 1.075 | 44.70 | 72.17 | 1.102 | 44.46 |
| 45 Kcps | 68.91 | 1.052 | 44.70 | 71.24 | 1.088 | 44.46 | 73.10 | 1.116 | 44.23 |
| 50 Kcps | 69.61 | 1.063 | 44.58 | 72.52 | 1.107 | 44.23 | 74.15 | 1.132 | 44.12 |
| 55 Kcps | 69.96 | 1.068 | 44.23 | 72.87 | 1.113 | 44.00 | 75.31 | 1.150 | 43.80 |
| 60 Kcps | 70.19 | 1.072 | 44.23 | 73.57 | 1.123 | 43.88 | 76.48 | 1.168 | 44.00 |
| 65 Kcps | 70.43 | 1.075 | 44.12 | 74.15 | 1.132 | 43.77 | 77.64 | 1.185 | 44.00 |
| 70 Kcps | 70.66 | 1.079 | 44.00 | 74.85 | 1.143 | 43.88 | 78.69 | 1.201 | 43.88 |
| 75 Kcps | 70.89 | 1.082 | 43.88 | 75.66 | 1.155 | 43.88 | 79.74 | 1.217 | 43.88 |
| 80 Kcps | 71.24 | 1.088 | 43.77 | 76.48 | 1.168 | 43.88 | 80.67 | 1.232 | 43.77 |
| 85 Kcps | 71.59 | 1.093 | 44.00 | 77.64 | 1.185 | 43.88 | 81.83 | 1.249 | 43.77 |
| 90 Kcps | 72.29 | 1.104 | 43.88 | 78.69 | 1.201 | 43.88 | 83.00 | 1.267 | 43.88 |
| 95 Kcps | 72.87 | 1.113 | 43.88 | 80.09 | 1.223 | 43.88 | 84.74 | 1.294 | 43.65 |
| 100 Kcps | 73.34 | 1.119 | 43.88 | 81.25 | 1.240 | 43.88 | 86.14 | 1.315 | 43.65 |

## Table 17. Chloroform(A)-Benzene(B) Mixture

| Volume Percent(A) | Mole Percent(A) | Refractive Index |
|---|---|---|
| 0 | 0.00 | 1.4949 |
| 5 | 5.52 | 1.4919 |
| 10 | 10.99 | 1.4889 |
| 15 | 16.39 | 1.4859 |
| 20 | 21.74 | 1.4830 |
| 25 | 26.88 | 1.4802 |
| 30 | 32.26 | 1.4773 |
| 35 | 37.43 | 1.4744 |
| 40 | 42.55 | 1.4716 |
| 45 | 47.62 | 1.4689 |
| 50 | 52.63 | 1.4661 |
| 55 | 57.59 | 1.4634 |
| 60 | 62.50 | 1.4607 |
| 65 | 67.36 | 1.4581 |
| 70 | 72.77 | 1.4551 |
| 75 | 77.56 | 1.4525 |
| 80 | 81.63 | 1.4503 |
| 85 | 86.29 | 1.4473 |
| 90 | 90.91 | 1.4452 |
| 95 | 95.48 | 1.4427 |
| 100 | 100.00 | 1.4402 |

| Mole Percent(A) |  |  |
|---|---|---|
| Liquid | Vapor | Temperature, °C |
| 0 | 0 | 80.6 |
| 8 | 10 | 79.8 |
| 15 | 20 | 79.0 |
| 22 | 30 | 78.2 |
| 29 | 40 | 77.3 |
| 36 | 50 | 76.4 |
| 44 | 60 | 75.3 |
| 54 | 70 | 74.0 |
| 66 | 80 | 71.9 |
| 79 | 90 | 68.9 |
| 100 | 100 | 61.4 |

Mole Percent(A) = 2732.91 - (1828.15)*(Refractive Index)

## Table 18. Chloroform(A)-Benzene(B) Mixture Experimental Data

| Position | Bottom | | | | Middle | | | |
|---|---|---|---|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 67.4 | 77.5 | 1.4535 | 1.4696 | 67.4 | 77.5 | 1.4535 | 1.4696 |
| 25 Kcps | 67.1 | 77.5 | 1.4535 | 1.4696 | 67.3 | 77.5 | 1.4535 | 1.4695 |
| 30 Kcps | 66.9 | 77.5 | 1.4535 | 1.4695 | 66.8 | 77.5 | 1.4532 | 1.4696 |
| 35 Kcps | 66.7 | 77.5 | 1.4533 | 1.4695 | 66.1 | 77.5 | 1.4528 | 1.4695 |
| 40 Kcps | 66.4 | 77.5 | 1.4531 | 1.4695 | 65.6 | 77.5 | 1.4523 | 1.4695 |
| 45 Kcps | 65.7 | 77.5 | 1.4525 | 1.4695 | 65.1 | 77.5 | 1.4517 | 1.4696 |
| 50 Kcps | 65.4 | 77.5 | 1.4520 | 1.4695 | 64.7 | 77.5 | 1.4510 | 1.4696 |
| 55 Kcps | 65.0 | 77.5 | 1.4514 | 1.4695 | 64.0 | 77.5 | 1.4499 | 1.4696 |
| 60 Kcps | 64.1 | 77.5 | 1.4507 | 1.4695 | 63.6 | 77.5 | 1.4487 | 1.4696 |
| 65 Kcps | 63.7 | 77.5 | 1.4499 | 1.4696 | 63.1 | 77.5 | 1.4476 | 1.4697 |
| 70 Kcps | 63.0 | 77.5 | 1.4492 | 1.4696 | 62.4 | 77.5 | 1.4460 | 1.4696 |
| 75 Kcps | 62.8 | 77.5 | 1.4483 | 1.4696 | 61.8 | 77.5 | 1.4445 | 1.4696 |
| 80 Kcps | 62.4 | 77.5 | 1.4476 | 1.4695 | 61.0 | 77.5 | 1.4435 | 1.4697 |
| 85 Kcps | 61.2 | 77.5 | 1.4468 | 1.4695 | 60.7 | 77.5 | 1.4427 | 1.4696 |
| 90 Kcps | 60.9 | 77.5 | 1.4459 | 1.4695 | 60.3 | 77.5 | 1.4420 | 1.4696 |
| 95 Kcps | 60.7 | 77.5 | 1.4448 | 1.4696 | 60.1 | 77.5 | 1.4416 | 1.4695 |
| 100 Kcps | 60.2 | 77.5 | 1.4443 | 1.4696 | 60.2 | 77.5 | 1.4420 | 1.4695 |

# Table 18. Chloroform(A)-Benzene(B) Mixture Experimental Data - Cont'd

## Top

| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
|---|---|---|---|---|
| 20 Kcps | 67.4 | 77.5 | 1.4533 | 1.4695 |
| 25 Kcps | 67.0 | 77.5 | 1.4526 | 1.4695 |
| 30 Kcps | 66.7 | 77.5 | 1.4519 | 1.4695 |
| 35 Kcps | 65.3 | 77.5 | 1.4511 | 1.4696 |
| 40 Kcps | 64.1 | 77.5 | 1.4501 | 1.4696 |
| 45 Kcps | 63.6 | 77.5 | 1.4486 | 1.4696 |
| 50 Kcps | 63.1 | 77.5 | 1.4470 | 1.4696 |
| 55 Kcps | 62.6 | 77.5 | 1.4460 | 1.4697 |
| 60 Kcps | 62.1 | 77.5 | 1.4443 | 1.4696 |
| 65 Kcps | 61.7 | 77.5 | 1.4434 | 1.4697 |
| 70 Kcps | 60.8 | 77.5 | 1.4427 | 1.4697 |
| 75 Kcps | 60.2 | 77.5 | 1.4421 | 1.4697 |
| 80 Kcps | 59.8 | 77.5 | 1.4418 | 1.4696 |
| 85 Kcps | 59.7 | 77.5 | 1.4414 | 1.4697 |
| 90 Kcps | 60.0 | 77.5 | 1.4416 | 1.4696 |
| 95 Kcps | 60.3 | 77.5 | 1.4418 | 1.4696 |
| 100 Kcps | 60.6 | 77.5 | 1.4423 | 1.4695 |

## Table 19. Chloroform(A)-Benzene(B) Mixture Separation Factors

| | Bottom | | | Middle | | |
|---|---|---|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 75.96 | 0.760 | 46.26 | 75.96 | 0.760 | 46.26 |
| 25 Kcps | 75.96 | 0.760 | 46.26 | 75.96 | 0.760 | 46.44 |
| 30 Kcps | 75.96 | 0.760 | 46.44 | 76.24 | 0.762 | 46.26 |
| 35 Kcps | 76.06 | 0.761 | 46.44 | 76.97 | 0.770 | 46.44 |
| 40 Kcps | 76.43 | 0.764 | 46.44 | 77.89 | 0.779 | 46.44 |
| 45 Kcps | 77.52 | 0.775 | 46.44 | 78.98 | 0.790 | 46.26 |
| 50 Kcps | 78.44 | 0.784 | 46.44 | 80.26 | 0.803 | 46.26 |
| 55 Kcps | 79.53 | 0.795 | 46.44 | 82.28 | 0.823 | 46.26 |
| 60 Kcps | 80.81 | 0.808 | 46.44 | 84.47 | 0.845 | 46.26 |
| 65 Kcps | 82.28 | 0.823 | 46.26 | 86.48 | 0.865 | 46.08 |
| 70 Kcps | 83.56 | 0.836 | 46.26 | 89.41 | 0.894 | 46.26 |
| 75 Kcps | 85.20 | 0.852 | 46.26 | 92.15 | 0.922 | 46.26 |
| 80 Kcps | 86.48 | 0.865 | 46.44 | 93.98 | 0.940 | 46.08 |
| 85 Kcps | 87.94 | 0.879 | 46.44 | 95.44 | 0.954 | 46.26 |
| 90 Kcps | 89.59 | 0.896 | 46.44 | 96.72 | 0.967 | 46.26 |
| 95 Kcps | 91.60 | 0.916 | 46.26 | 97.45 | 0.975 | 46.44 |
| 100 Kcps | 92.51 | 0.925 | 46.26 | 97.08 | 0.971 | 46.44 |

## Table 19. Chloroform(A)-Benzene(B) Mixture Separation Factors - Cont'd

| Frequency | $Y_A$ | Top<br>$F_A$ | $X_A$ |
|---|---|---|---|
| 20 Kcps | 76.06 | 0.761 | 46.44 |
| 25 Kcps | 77.34 | 0.773 | 46.44 |
| 30 Kcps | 78.62 | 0.786 | 46.44 |
| 35 Kcps | 80.08 | 0.801 | 46.26 |
| 40 Kcps | 81.91 | 0.819 | 46.26 |
| 45 Kcps | 84.69 | 0.847 | 46.26 |
| 50 Kcps | 87.58 | 0.876 | 46.26 |
| 55 Kcps | 89.41 | 0.894 | 46.08 |
| 60 Kcps | 92.51 | 0.925 | 46.26 |
| 65 Kcps | 94.16 | 9.942 | 46.08 |
| 70 Kcps | 95.44 | 0.954 | 46.08 |
| 75 Kcps | 96.53 | 0.965 | 46.08 |
| 80 Kcps | 97.08 | 0.971 | 46.26 |
| 85 Kcps | 97.81 | 0.978 | 46.08 |
| 90 Kcps | 97.45 | 0.975 | 46.26 |
| 95 Kcps | 97.08 | 0.971 | 47.26 |
| 100 Kcps | 96.72 | 0.967 | 46.44 |

Table 20. Chloroform(A)-Ethanol(B) Mixture

| Volume Percent(A) | Mole Percent(A) | Refractive Index |
|---|---|---|
| 0 | 0.00 | 1.3574 |
| 5 | 3.70 | 1.3605 |
| 10 | 7.51 | 1.3636 |
| 15 | 11.43 | 1.3669 |
| 20 | 15.45 | 1.3702 |
| 25 | 19.59 | 1.3736 |
| 30 | 23.85 | 1.3771 |
| 35 | 28.24 | 1.3808 |
| 40 | 32.77 | 1.3845 |
| 45 | 37.43 | 1.3884 |
| 50 | 42.23 | 1.3924 |
| 55 | 47.19 | 1.3965 |
| 60 | 52.30 | 1.4071 |
| 65 | 57.28 | 1.4051 |
| 70 | 63.04 | 1.4096 |
| 75 | 68.68 | 1.4143 |
| 80 | 74.52 | 1.4191 |
| 85 | 80.55 | 1.4241 |
| 90 | 86.81 | 1.4293 |
| 95 | 93.28 | 1.4346 |
| 100 | 100.00 | 1.4402 |

| Mole Percent(B) | Temperature,°C |
|---|---|
| 0 | 60.95 |
| 7 | 59.1 |
| 15 | 59.6 |
| 30 | 61.4 |
| 40 | 63.3 |
| 50 | 65.7 |
| 60 | 68.4 |
| 70 | 71.0 |
| 80 | 73.6 |
| 90 | 75.8 |
| 100 | 77.9 |

Minimum boiling point azeotropic binary mixture at 84 mole percent(A) and 59.3°C.

Mole Percent(A) = (1207.73)*(Refractive Index) - 1639.37

## Table 21. Chloroform(A)-Ethanol(B) Mixture Experimental Data

| Position | Bottom | | | | Middle | | | |
|---|---|---|---|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 58.2 | 61.6 | 1.4123 | 1.3865 | 58.2 | 61.6 | 1.4123 | 1.3865 |
| 25 Kcps | 58.2 | 61.6 | 1.4133 | 1.3865 | 58.1 | 61.6 | 1.4134 | 1.3865 |
| 30 Kcps | 58.2 | 61.6 | 1.4141 | 1.3865 | 58.0 | 61.6 | 1.4145 | 1.3865 |
| 35 Kcps | 58.2 | 61.6 | 1.4146 | 1.3865 | 58.0 | 61.6 | 1.4154 | 1.3865 |
| 40 Kcps | 58.1 | 61.6 | 1.4152 | 1.3865 | 58.0 | 61.6 | 1.4163 | 1.3865 |
| 45 Kcps | 58.1 | 61.6 | 1.4156 | 1.3865 | 58.0 | 61.6 | 1.4171 | 1.3865 |
| 50 Kcps | 58.2 | 61.6 | 1.4158 | 1.3865 | 58.0 | 61.6 | 1.4181 | 1.3866 |
| 55 Kcps | 58.2 | 61.6 | 1.4163 | 1.3866 | 57.9 | 61.6 | 1.4190 | 1.3865 |
| 60 Kcps | 58.2 | 61.6 | 1.4172 | 1.3866 | 57.8 | 61.6 | 1.4199 | 1.3865 |
| 65 Kcps | 58.2 | 61.6 | 1.4173 | 1.3865 | 57.5 | 61.6 | 1.4206 | 1.3865 |
| 70 Kcps | 58.2 | 61.6 | 1.4173 | 1.3865 | 57.6 | 61.6 | 1.4211 | 1.3866 |
| 75 Kcps | 58.2 | 61.6 | 1.4174 | 1.3865 | 57.5 | 61.6 | 1.4215 | 1.3866 |
| 80 Kcps | 58.2 | 61.6 | 1.4174 | 1.3865 | 57.3 | 61.6 | 1.4222 | 1.3865 |
| 85 Kcps | 58.2 | 61.6 | 1.4175 | 1.3866 | 57.2 | 61.6 | 1.4231 | 1.3865 |
| 90 Kcps | 58.2 | 61.6 | 1.4175 | 1.3865 | 57.1 | 61.6 | 1.4236 | 1.3866 |
| 95 Kcps | 58.2 | 61.6 | 1.4175 | 1.3865 | ---- | ---- | ----- | ----- |
| 100 Kcps | 58.1 | 61.6 | 1.4176 | 1.3865 | ---- | ---- | ----- | ----- |

Table 21. Chloroform(A)-Ethanol(B) Mixture Experimental Data - Cont'd

| Position | Top | | | |
|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 58.2 | 61.6 | 1.4125 | 1.3865 |
| 25 Kcps | 58.1 | 61.6 | 1.4149 | 1.3865 |
| 30 Kcps | 58.1 | 61.6 | 1.4174 | 1.3865 |
| 35 Kcps | 58.0 | 61.6 | 1.4183 | 1.3866 |
| 40 Kcps | 57.8 | 61.6 | 1.4203 | 1.6866 |
| 45 Kcps | 57.5 | 61.6 | 1.4216 | 1.3865 |
| 50 Kcps | 57.4 | 61.6 | 1.4229 | 1.3865 |
| 55 Kcps | 57.2 | 61.6 | 1.4229 | 1.3865 |
| 60 Kcps | 57.1 | 61.6 | 1.4236 | 1.3865 |
| 65 Kcps | ---- | ---- | ------ | ------ |
| 70 Kcps | ---- | ---- | ------ | ------ |
| 75 Kcps | ---- | ---- | ------ | ------ |
| 80 Kcps | ---- | ---- | ------ | ------ |
| 85 Kcps | ---- | ---- | ------ | ------ |
| 90 Kcps | ---- | ---- | ------ | ------ |
| 95 Kcps | ---- | ---- | ------ | ------ |
| 100 Kcps | ---- | ---- | ------ | ------ |

## Table 22. Chloroform(A)-Ethanol(B) Mixture Separation Factors

| Position | Bottom | | | Middle | | |
|---|---|---|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 66.31 | 0.789 | 35.15 | 66.31 | 0.789 | 35.15 |
| 25 Kcps | 67.51 | 0.803 | 35.15 | 67.64 | 0.805 | 35.15 |
| 30 Kcps | 68.48 | 0.815 | 35.15 | 68.96 | 0.821 | 35.15 |
| 35 Kcps | 69.08 | 0.822 | 35.15 | 70.05 | 0.834 | 35.15 |
| 40 Kcps | 69.81 | 0.831 | 35.15 | 71.14 | 0.847 | 35.15 |
| 45 Kcps | 70.29 | 0.837 | 35.15 | 72.10 | 0.858 | 35.15 |
| 50 Kcps | 70.53 | 0.839 | 35.15 | 73.31 | 0.872 | 35.27 |
| 55 Kcps | 71.14 | 0.847 | 35.27 | 74.40 | 0.885 | 35.15 |
| 60 Kcps | 72.22 | 0.859 | 35.27 | 75.49 | 0.898 | 35.15 |
| 65 Kcps | 72.35 | 0.861 | 35.15 | 76.33 | 0.908 | 35.35 |
| 70 Kcps | 72.35 | 0.861 | 35.15 | 76.94 | 0.916 | 35.27 |
| 75 Kcps | 72.47 | 0.862 | 35.15 | 77.42 | 0.921 | 35.27 |
| 80 Kcps | 72.51 | 0.863 | 35.15 | 78.26 | 0.931 | 35.15 |
| 85 Kcps | 72.59 | 0.864 | 35.27 | 79.35 | 0.944 | 35.15 |
| 90 Kcps | 72.59 | 0.864 | 35.15 | 79.95 | 0.951 | 35.27 |
| 95 Kcps | 72.59 | 0.864 | 35.15 | ----- | ----- | ----- |
| 100 Kcps | 72.71 | 0.865 | 35.15 | ----- | ----- | ----- |

Table 22. Chloroform(A)-Ethanol(B) Mixture Separation Factors - Cont'd

| Position | | Top | |
|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 66.55 | 0.791 | 35.15 |
| 25 Kcps | 69.48 | 0.827 | 35.15 |
| 30 Kcps | 72.47 | 0.862 | 35.15 |
| 35 Kcps | 73.55 | 0.875 | 35.27 |
| 40 Kcps | 75.97 | 0.904 | 35.27 |
| 45 Kcps | 77.54 | 0.923 | 35.15 |
| 50 Kcps | 79.11 | 0.941 | 35.15 |
| 55 Kcps | 79.11 | 0.941 | 35.15 |
| 60 Kcps | 79.95 | 0.951 | 35.15 |
| 65 Kcps | ----- | ----- | ----- |
| 70 Kcps | ----- | ----- | ----- |
| 75 Kcps | ----- | ----- | ----- |
| 80 Kcps | ----- | ----- | ----- |
| 85 Kcps | ----- | ----- | ----- |
| 90 Kcps | ----- | ----- | ----- |
| 95 Kcps | ----- | ----- | ----- |
| 100 Kcps | ----- | ----- | ----- |

## Table 23. Ethanol(A)-Water(B) Mixture

| Volume Percent(A) | Mole Percent(A) | Refractive Index |
|---|---|---|
| 0 | 0.00 | 1.3314 |
| 5 | 1.59 | 1.3318 |
| 10 | 3.31 | 1.3323 |
| 15 | 5.15 | 1.3327 |
| 20 | 7.15 | 1.3333 |
| 25 | 9.29 | 1.3338 |
| 30 | 11.66 | 1.3344 |
| 35 | 14.23 | 1.3351 |
| 40 | 17.03 | 1.3358 |
| 45 | 20.12 | 1.3366 |
| 50 | 23.54 | 1.3375 |
| 55 | 27.36 | 1.3385 |
| 60 | 31.61 | 1.3396 |
| 65 | 36.39 | 1.3409 |
| 70 | 41.82 | 1.3423 |
| 75 | 48.03 | 1.3439 |
| 80 | 55.18 | 1.3457 |
| 85 | 63.59 | 1.3479 |
| 90 | 73.48 | 1.3505 |
| 95 | 85.39 | 1.3536 |
| 100 | 100.00 | 1.3574 |

| Mole Percent(A) Liquid | Mole Percent(A) Vapor | Temperature, °C |
|---|---|---|
| 0.00 | 0.00 | 100.0 |
| 1.90 | 17.00 | 95.5 |
| 7.21 | 38.91 | 89.0 |
| 9.66 | 43.75 | 86.7 |
| 12.38 | 47.04 | 85.3 |
| 16.61 | 50.89 | 84.1 |
| 23.37 | 54.45 | 82.7 |
| 26.08 | 55.80 | 82.3 |
| 32.73 | 58.26 | 81.5 |
| 39.65 | 61.22 | 80.7 |
| 50.79 | 65.64 | 79.8 |
| 51.98 | 65.99 | 79.7 |
| 57.32 | 68.41 | 79.3 |
| 67.63 | 73.85 | 78.74 |
| 74.72 | 78.15 | 78.41 |
| 89.43 | 89.43 | 78.15 |

Mole Percent(A) = (3846.15)*(Refractive Index) - 5120.77

## Table 24. Ethanol(A)-Water(B) Mixture Experimental Data

| Position | Bottom | | | | Middle | | | |
|---|---|---|---|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 76.2 | 87.4 | 1.3507 | 1.3335 | 76.2 | 87.4 | 1.3507 | 1.3335 |
| 25 Kcps | 76.3 | 87.4 | 1.3507 | 1.3335 | 76.2 | 87.4 | 1.3512 | 1.3335 |
| 30 Kcps | 76.2 | 87.3 | 1.3508 | 1.3335 | 76.3 | 87.3 | 1.3515 | 1.3335 |
| 35 Kcps | 76.1 | 87.3 | 1.3511 | 1.3335 | 76.2 | 87.4 | 1.3521 | 1.3335 |
| 40 Kcps | 76.0 | 87.4 | 1.3516 | 1.3335 | 76.1 | 87.3 | 1.3526 | 1.3335 |
| 45 Kcps | 75.8 | 87.4 | 1.3520 | 1.3335 | 75.8 | 87.4 | 1.3530 | 1.3336 |
| 50 Kcps | 75.8 | 87.4 | 1.3521 | 1.3335 | 75.6 | 87.3 | 1.3532 | 1.3335 |
| 55 Kcps | 75.8 | 87.3 | 1.3521 | 1.3335 | 75.6 | 87.3 | 1.3534 | 1.3335 |
| 60 Kcps | 75.8 | 87.3 | 1.3522 | 1.3336 | 75.6 | 87.3 | 1.3535 | 1.3336 |
| 65 Kcps | 75.7 | 87.3 | 1.3523 | 1.3335 | 75.4 | 87.4 | 1.3537 | 1.3336 |
| 70 Kcps | 75.8 | 87.3 | 1.3523 | 1.3335 | 75.4 | 87.4 | 1.3538 | 1.3336 |
| 75 Kcps | 75.8 | 87.3 | 1.3524 | 1.3335 | 75.5 | 87.4 | 1.3539 | 1.3335 |
| 80 Kcps | 75.8 | 87.4 | 1.3525 | 1.3336 | 75.6 | 87.4 | 1.3540 | 1.3335 |
| 85 Kcps | 75.8 | 87.3 | 1.3526 | 1.3336 | 75.6 | 87.4 | 1.3542 | 1.3336 |
| 90 Kcps | 75.8 | 87.4 | 1.3527 | 1.3335 | 75.7 | 87.4 | 1.3542 | 1.3335 |
| 95 Kcps | 75.9 | 87.4 | 1.3527 | 1.3335 | 75.8 | 87.4 | 1.3544 | 1.3336 |
| 100 Kcps | 76.1 | 87.4 | 1.3528 | 1.3335 | 76.0 | 87.4 | 1.3545 | 1.3336 |

## Table 24. Ethanol(A)-Water(B) Mixture Experimental Data - Cont'd

| Position | Top | | | |
|---|---|---|---|---|
| Frequency | $T_o$ | $T_b$ | $R_o$ | $R_b$ |
| 20 Kcps | 76.2 | 87.5 | 1.3508 | 1.3336 |
| 25 Kcps | 75.9 | 87.6 | 1.3511 | 1.3336 |
| 30 Kcps | 75.3 | 87.5 | 1.3517 | 1.3337 |
| 35 Kcps | 74.8 | 87.4 | 1.3534 | 1.3337 |
| 40 Kcps | 74.1 | 87.6 | 1.3547 | 1.3336 |
| 45 Kcps | 74.2 | 87.5 | 1.3564 | 1.3336 |
| 50 Kcps | 74.4 | 87.5 | 1.3567 | 1.3336 |
| 55 Kcps | 74.6 | 87.5 | 1.3567 | 1.3337 |
| 60 Kcps | 75.0 | 87.4 | 1.3568 | 1.3337 |
| 65 Kcps | 75.0 | 87.4 | 1.3569 | 1.3337 |
| 70 Kcps | 75.2 | 87.3 | 1.3568 | 1.3336 |
| 75 Kcps | 75.1 | 87.5 | 1.3568 | 1.3336 |
| 80 Kcps | 75.3 | 87.4 | 1.3567 | 1.3336 |
| 85 Kcps | 75.3 | 87.4 | 1.3568 | 1.3336 |
| 90 Kcps | 75.2 | 87.4 | 1.3569 | 1.3337 |
| 95 Kcps | 75.2 | 87.4 | 1.3569 | 1.3336 |
| 100 Kcps | 75.3 | 87.4 | 1.3569 | 1.3337 |

## Table 25. Ethanol(A)-Water(B) Misture Separation Factors

| Position | Bottom | | | Middle | | |
|---|---|---|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 74.23 | 0.950 | 8.07 | 74.23 | 0.950 | 8.07 |
| 25 Kcps | 74.23 | 0.950 | 8.07 | 76.15 | 0.975 | 8.07 |
| 30 Kcps | 74.61 | 0.955 | 8.07 | 77.30 | 0.989 | 8.07 |
| 35 Kcps | 75.76 | 0.970 | 8.07 | 79.61 | 1.019 | 8.07 |
| 40 Kcps | 77.69 | 0.994 | 8.07 | 81.53 | 1.044 | 8.07 |
| 45 Kcps | 79.22 | 1.014 | 8.07 | 83.07 | 1.063 | 8.46 |
| 50 Kcps | 79.61 | 1.019 | 8.07 | 83.84 | 1.073 | 8.07 |
| 55 Kcps | 79.61 | 1.019 | 8.07 | 84.61 | 1.083 | 8.07 |
| 60 Kcps | 79.99 | 1.024 | 8.46 | 84.99 | 1.088 | 8.46 |
| 65 Kcps | 80.38 | 1.029 | 8.07 | 85.76 | 1.098 | 8.46 |
| 70 Kcps | 80.38 | 1.029 | 8.07 | 86.15 | 1.103 | 8.46 |
| 75 Kcps | 80.76 | 1.034 | 8.07 | 86.53 | 1.108 | 8.07 |
| 80 Kcps | 81.15 | 1.039 | 8.46 | 86.92 | 1.113 | 8.07 |
| 85 Kcps | 81.53 | 1.044 | 8.46 | 87.69 | 1.122 | 8.46 |
| 90 Kcps | 81.92 | 1.049 | 8.07 | 87.69 | 1.122 | 8.07 |
| 95 Kcps | 81.92 | 1.049 | 8.07 | 88.46 | 1.132 | 8.46 |
| 100 Kcps | 82.30 | 1.053 | 8.07 | 88.84 | 1.137 | 8.46 |

Table 25. Ethanol(A)-Water(B) Mixture Separation Factors - Cont'd

| | | Top | |
|---|---|---|---|
| Frequency | $Y_A$ | $F_A$ | $X_A$ |
| 20 Kcps | 74.68 | 0.956 | 8.46 |
| 25 Kcps | 75.94 | 0.972 | 8.46 |
| 30 Kcps | 78.02 | 0.999 | 8.84 |
| 35 Kcps | 84.55 | 1.082 | 8.84 |
| 40 Kcps | 89.45 | 1.145 | 8.46 |
| 45 Kcps | 96.15 | 1.231 | 8.46 |
| 50 Kcps | 97.30 | 1.245 | 8.46 |
| 55 Kcps | 97.30 | 1.245 | 8.84 |
| 60 Kcps | 97.69 | 1.250 | 8.84 |
| 65 Kcps | 98.07 | 1.255 | 8.84 |
| 70 Kcps | 97.69 | 1.250 | 8.46 |
| 75 Kcps | 97.69 | 1.250 | 8.46 |
| 80 Kcps | 97.30 | 1.245 | 8.46 |
| 85 Kcps | 97.69 | 1.250 | 8.46 |
| 90 Kcps | 98.07 | 1.255 | 8.84 |
| 95 Kcps | 98.07 | 1.255 | 8.46 |
| 100 Kcps | 98.07 | 1.255 | 8.84 |

## ANALYSIS OF PACKING

The column was operated for 107 hours under normal or ultrasonic conditions. At the end of this period the packing was removed and examined for breakage. This examination revealed 4 berl saddles had been broken in the areas of the transducer (2 at the bottom, and 1 each at the middle and top). Because the packing was loaded with the column filled with water this breakage is a result of operation.

According to actual hand count there were 7,233 berl saddles loaded; this would mean a 0.0553% breakage due to operation. In most industrial applications ceramic packing is not used because of the superiority of plastic or metal packing; however, ceramic packing even when broken, offers good characteristics for separation. Packing reduced to dust can cause the pressure drop to increase substantially but there was no evidence of total destruction of any berl saddles because by actual count all the packing was accounted for.

Assuming approximately 3% breakage before the packing would be examined and/or replaced, an on stream time of 242 days of continuous operation can be expected. Of course the rate of packing deterioration may increase or decrease during operation and changing to a more flexible packing such as polypropylene should increase the on stream time; however, even the present operation can be used on an industrial level without incurring prohibitive initial and operating costs.

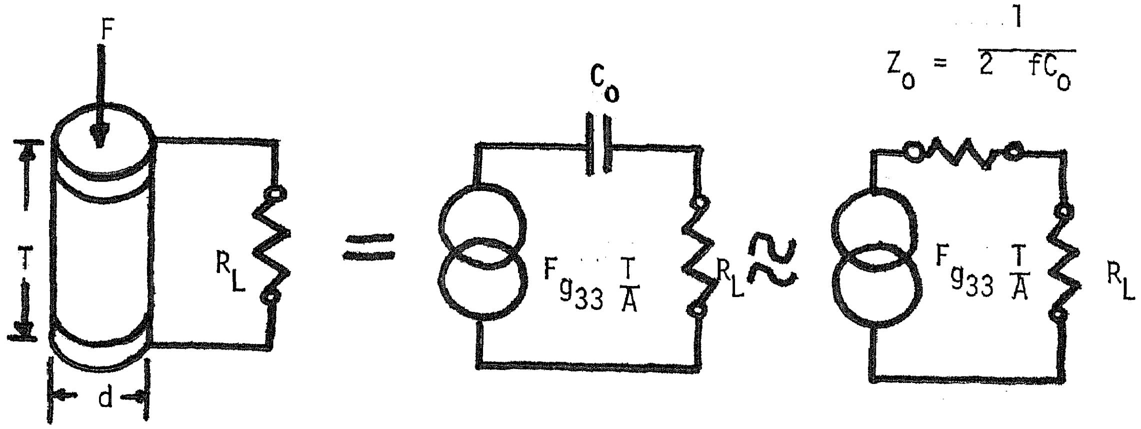
## DISCUSSION AND EVALUATION OF RESULTS

Six of the seven mixtures used for experimentation have azeotropic limitation so this composition at ambient pressure is defined as a separation factor of 1.000. For full range mixtures a separation factor of 1.000 corresponds to 100 mole percent in the overhead vapor.

Because the transducers are able to produce caviation in the liquid and sound waves in the vapor, it is assumed that these phenomena occur; however, observation of these phenomena are impossible when the column is lagged with asbestos tape. When the column was filled with water and before the ceramic packing was loaded, the two middle transducers were driven at 50 Kcps producing bubbles in the water which persisted long after residual dissolved air was liberated, indicating caviation was occuring near the wall. Combinations of three transducers were tried but no caviation was detected so only pairs of transducers were used during actual experimentation.

No measurements were made of actual power output of the amplifier which is rated at 50 watts because the determination of how much of this power was actually absorbed by the packing and the process streams was impossible. The use of more sophisticated techniques of sampling and power measurement could yield a correlation relating power consumption and separation which could be used to make an economic comparison of ultrasonic operation and other alternatives.

The energy relationships which may be used for transducers at frequencies well below resonance are:



$f \ll {}^{1}/(R{*}C_o)$:

for $R \leq Z_o$:

$W = \frac{V^2}{R} = (F_{avg}\ g_{33}\ \frac{T}{A})^2\ R\ \ /(R\ \ + Z_o)^2$ watts

for $R \ll Z_o$:

$W = (2\ f^{d}33\ F_{avg})^2\ \ R$ watts

for $t \ll R\ {*}C_o$:

$E = 1/2(C_o V_{oc}) = 1/2\ C_o * (F_{peak} g_{33}\ \frac{T}{A})$ Joules

for short circuit:

$E = (F_{avg}\ d_{33})^2\ \ R_L/t$ Joules

The results of the full range mixture are presented in Figure 9. and exhibit the same pattern as Figure 10., except there is a characteristic frequency at which increasing frequency has a negative effect on separation. This frequency must correspond to a pole (using an electrical analogy). The other systems probably have this same characteristic at some frequency outside the range used during this experimentation.

The minimum boiling azeotropic mixtures presented in the graphs (Figures 6., 7., 8., 11) show the overhead composition does not improve with increasing frequency once the azeotropic composition is reached. The slopes ($dF_A/df$) of the graphs can be related to the ease of separation below the azeotrope. For example, Figure 6. shows the slope remaining relatively constant for frequencies between 30-80 Kcps and independent of transducer position. Figures 7. and 11. show a fairly constant slope over the same frequency range but dependent on the transducer position. Figure 8. shows the most curvature over the entire frequency range indicating the slope is dependent on frequency and position. System 7., shown in Figure 12., is an exception to this pattern because the azeotropic temperature is less than 1°C from the normal boiling point of ethanol and small variations in pressure can affect this condition.

The maximum boiling azeotropic binary shown in Figure 10. has predictable results because decreasing temperature is favorable to continued separation once the azeotrope is passed. The slopes of

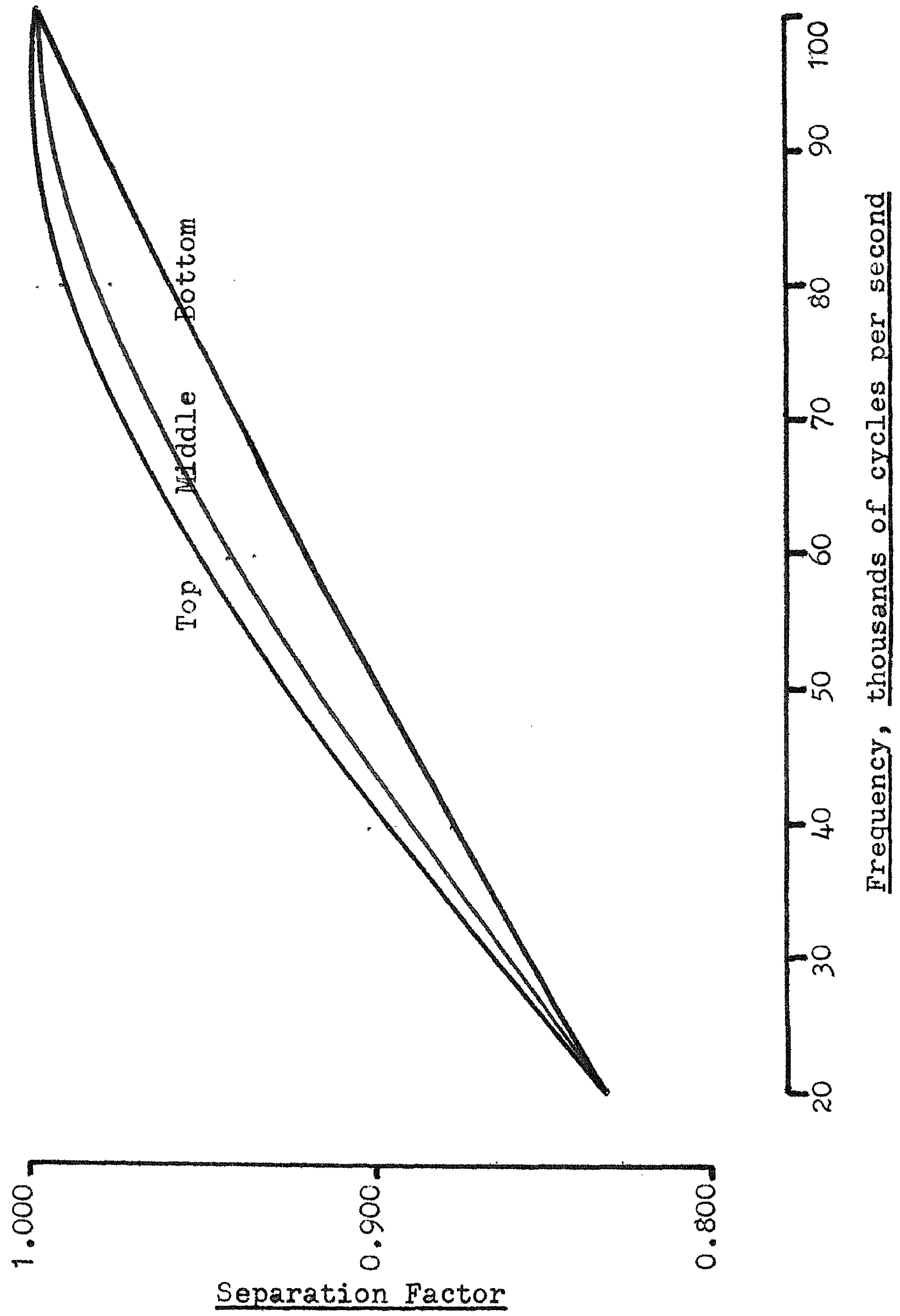


Figure 6; Separation Factor vs Frequency for $C_6H_6C_2H_5OH$

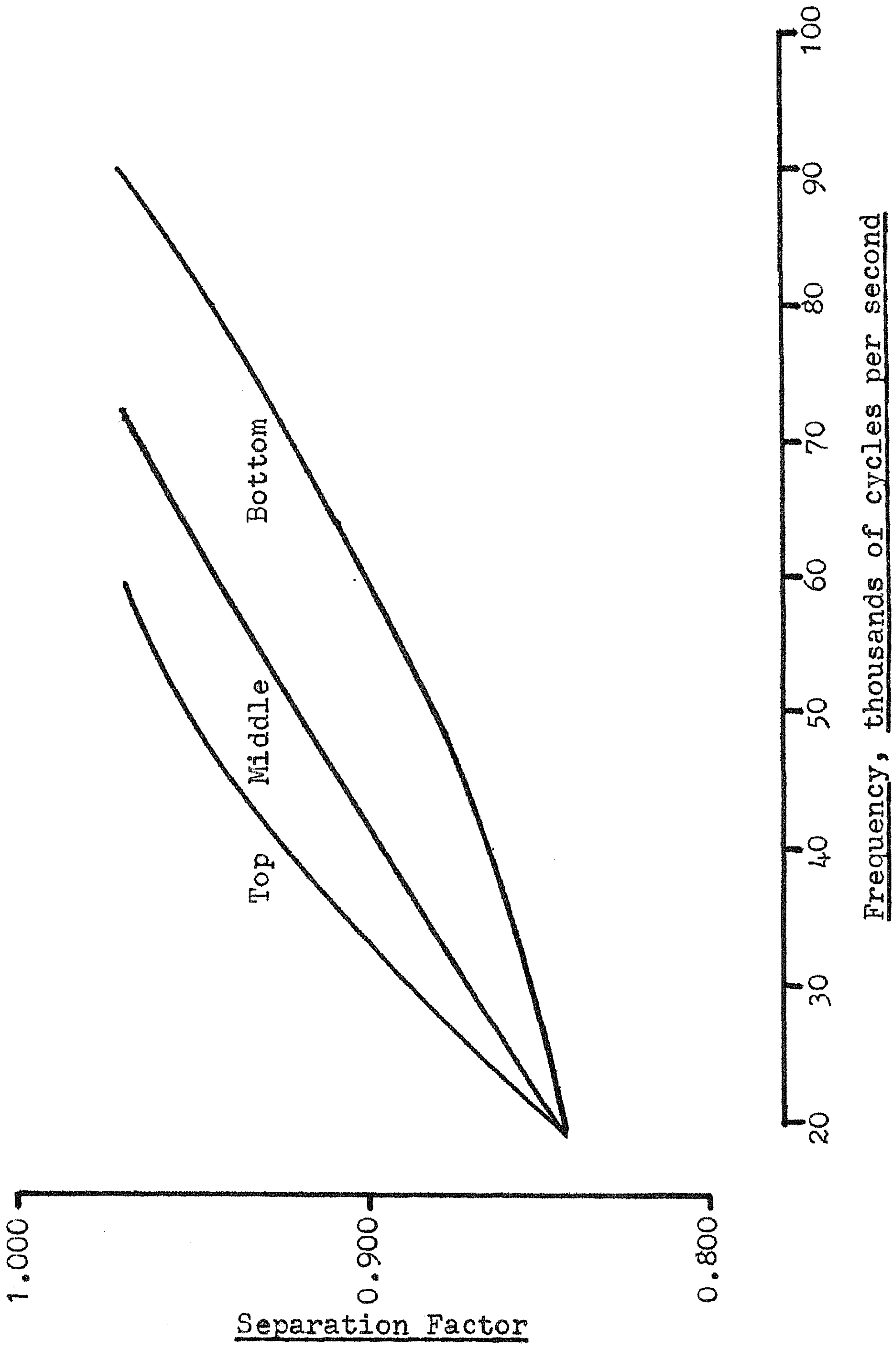


Figure 7. Separation Factor vs Frequency for $CCl_4$-$C_2H_5OH$

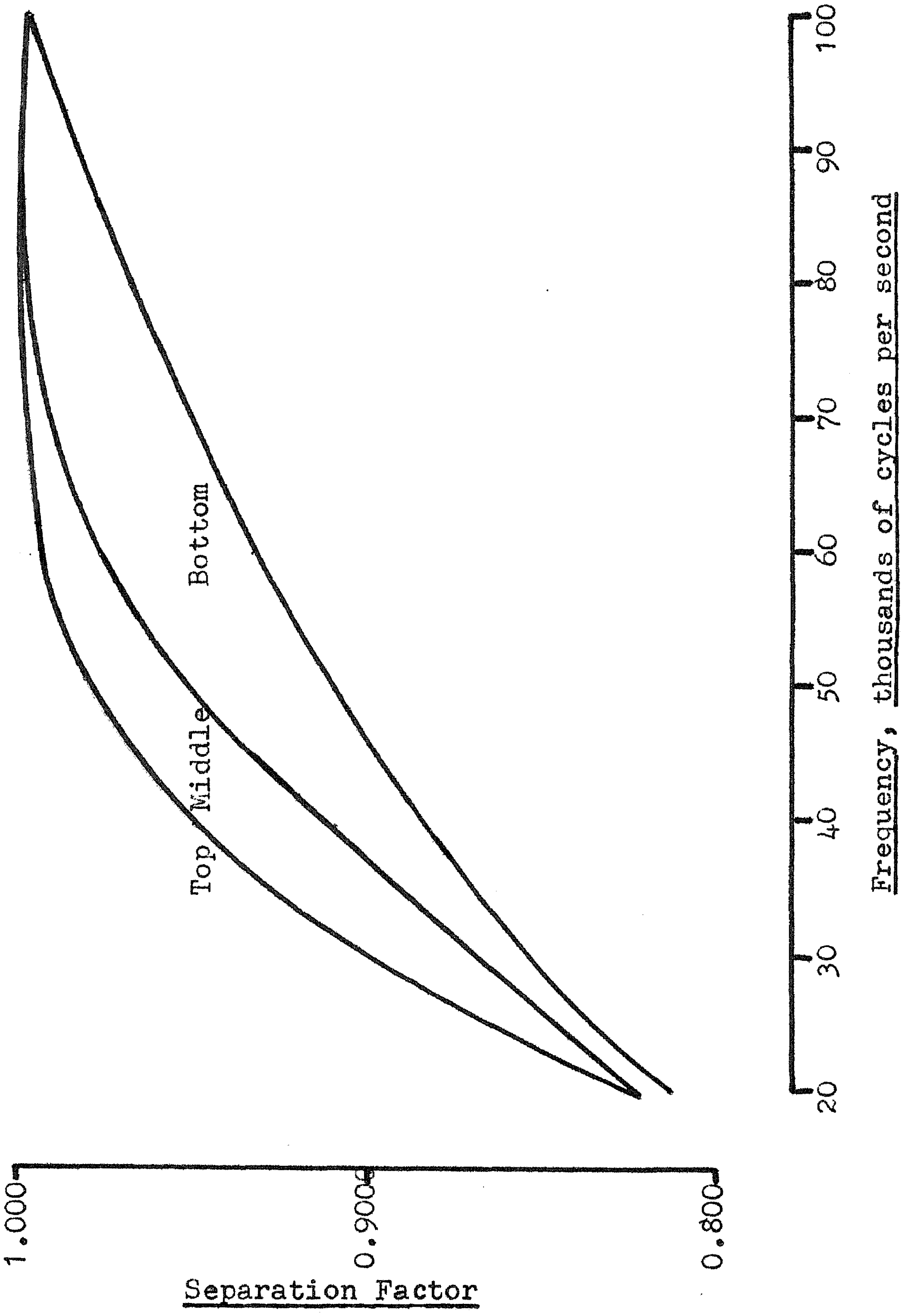


Figure 8. Separation Factor vs Frequency for $CCl_4$-$C_4H_{10}O_2$

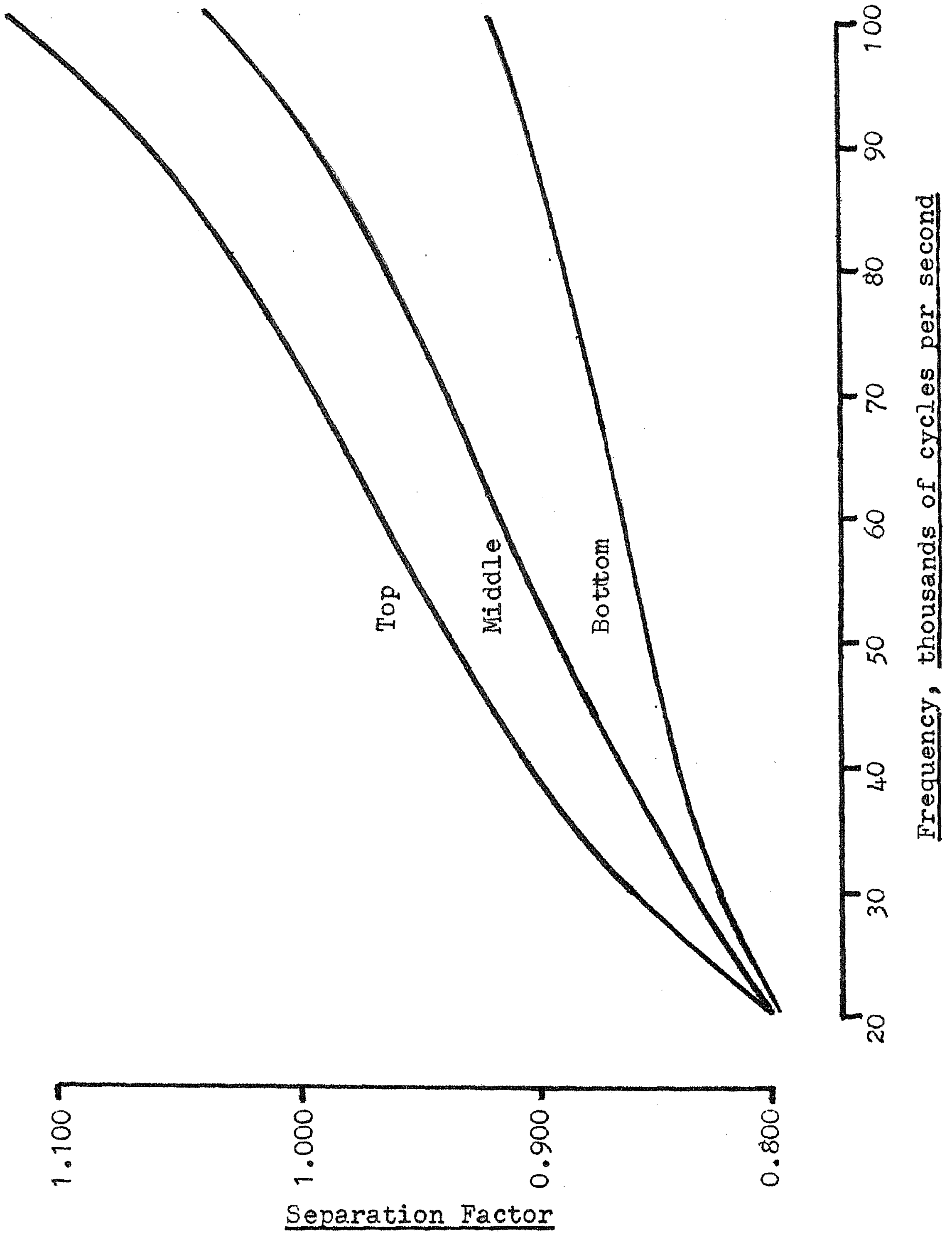


Figure 9. Separation Factor vs Frequency for $CHCl_3$-$C_3H_6O$

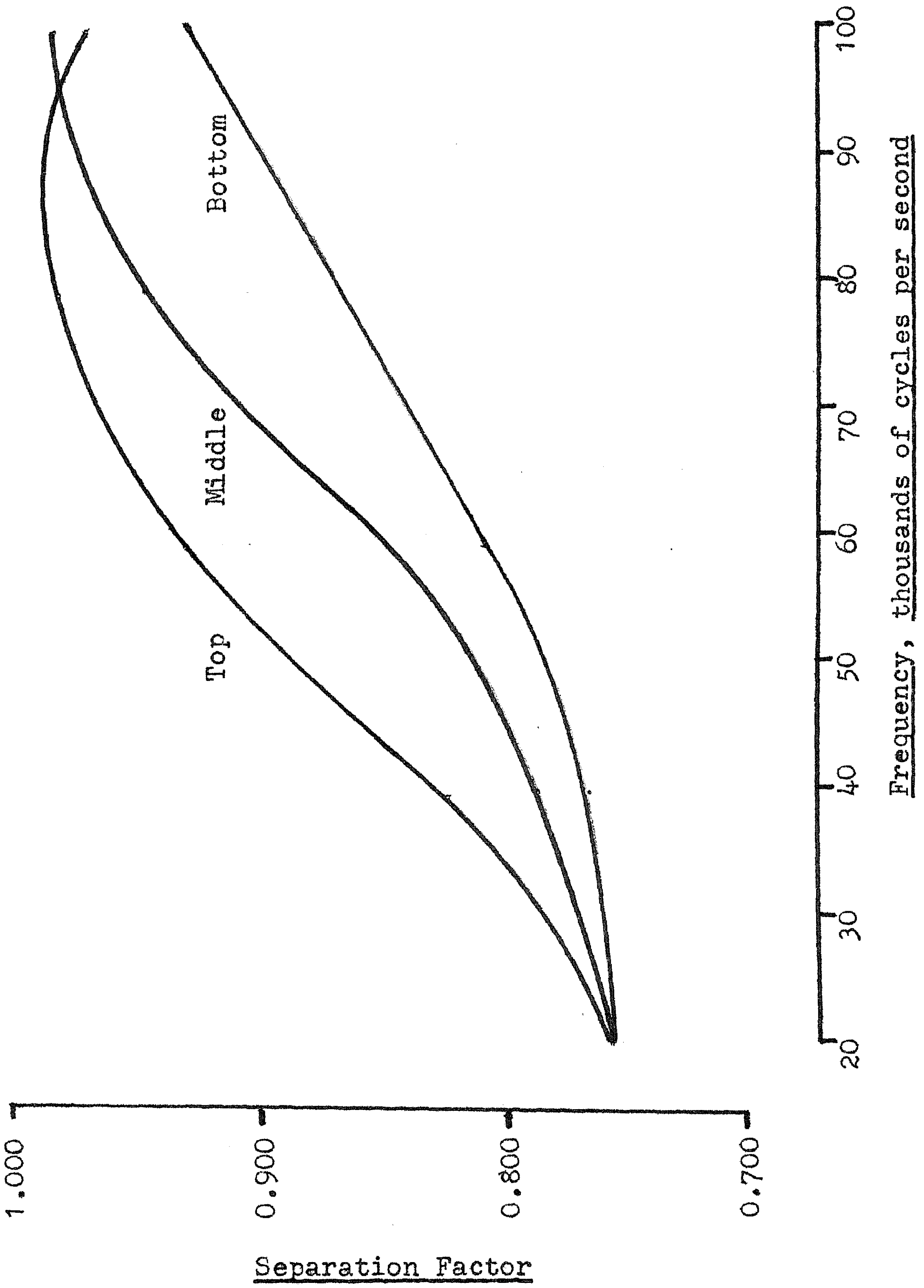


Figure 10. Separation Factor vs Frequency for $CHCl_3$-$C_6H_6$

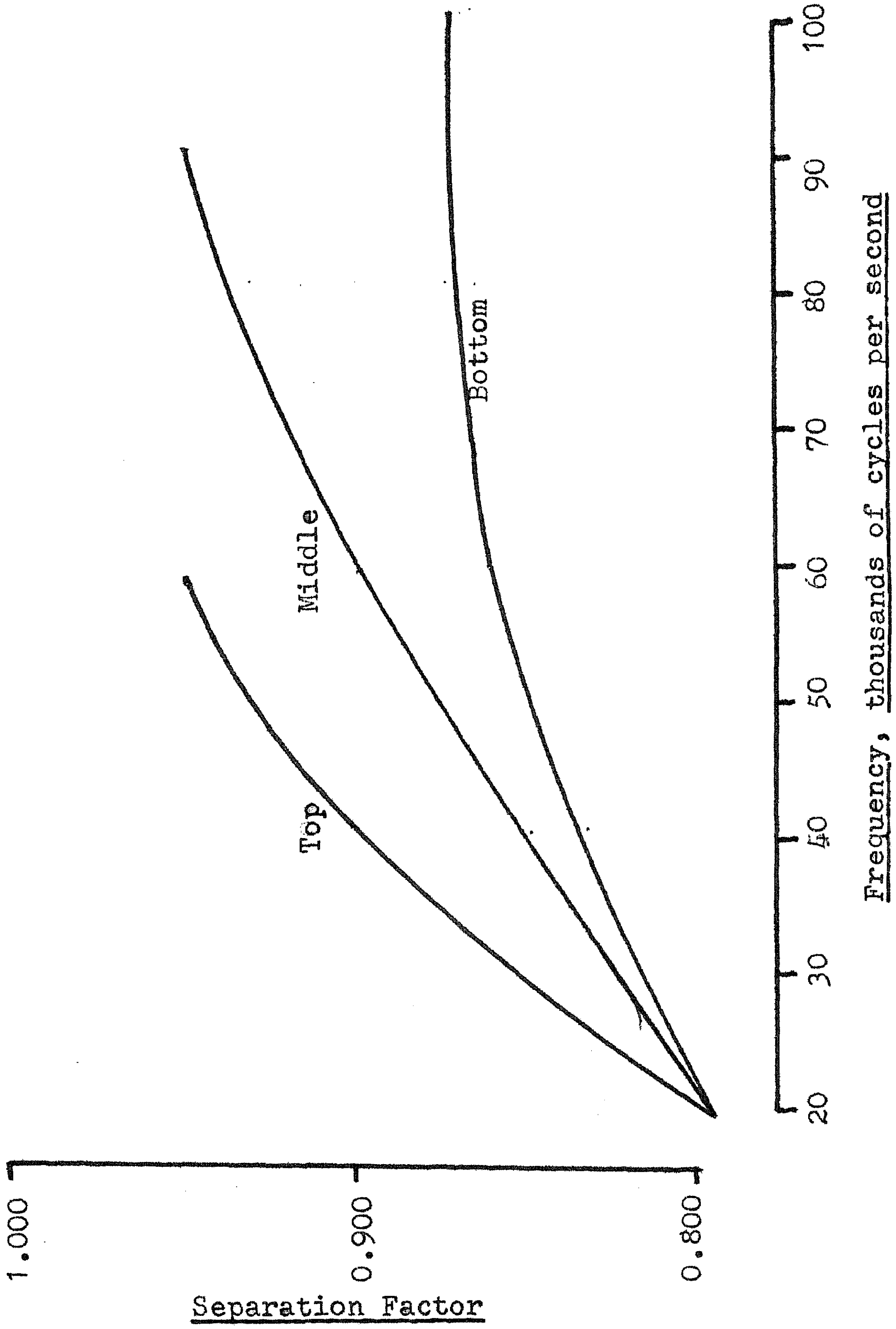


Figure 11. Separation Factor vs Frequency for $CHCl_3$-$C_2H_5OH$

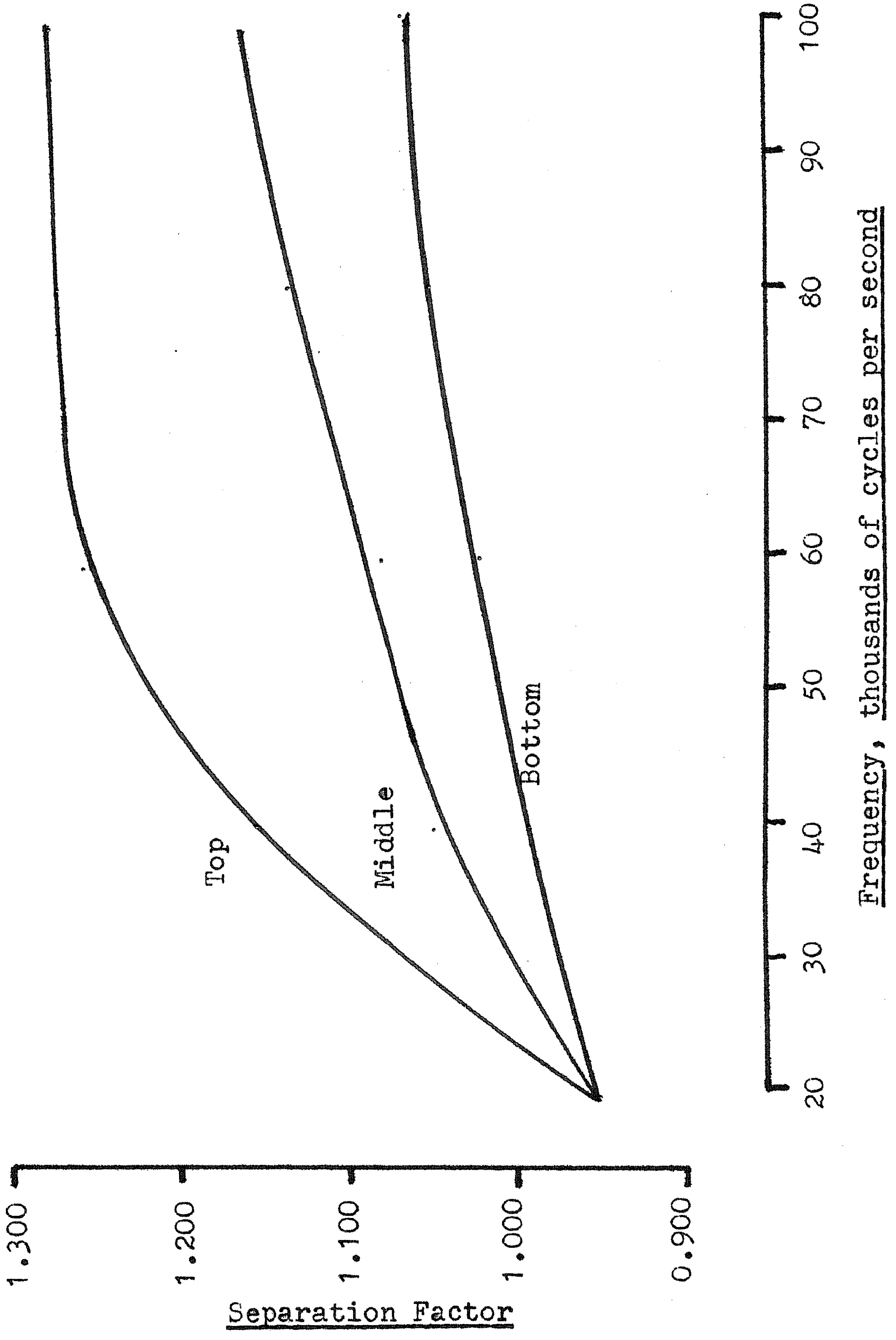


Figure 12. Separation Factor vs Frequency for $C_2H_5OH-H_2O$

these curves indicate continued separation can be expected as frequency is increased.

In conclusion, the experimentation has proven that improved separation will result if a packed column is excited by externally supplied ultrasonic energy. The principles which govern this improvement in separation are not well defined but can be partially explained by a combination of the following.

1. The velocity of the vapor and its direction are affected by the generation of high frequency sound waves and shock waves caused by caviation of the liquid.
2. The liquid loading as well as the path of the descending liquid are modified by the caviation of the liquid.
3. The arrangement of the packing is altered during ultrasonic operation which is evidenced by the presence of broken berl saddles in the areas of the transducers.

The above mentioned conditions are probably only a few of the many phenomena which occur in this quasi-steady state process. Only further experimentation can answer the questions which this experimentation has uncovered.

## AUTHOR'S COMMENTS ON SAFETY

Extreme caution must be taken when using high voltage amplifiers and flammable components. It must be noted that a transducer is a charged capacitor, and even though air, epoxy and glass are poor conductors, there is leakage which means a constant potential for arcing is present.

In order to achieve steady operation the system must be maintained at constant pressure, which in the case of the packed column meant using an atmospheric vent. Care must be taken to insure that flammable or toxic vapors do not accumulate causing a potential fire or health hazard.

Because the frequency is above the audible range, fatigue problems in the connections can be expected. All fittings should be epoxyed in place to decrease the possibility of leaking flammable or toxic streams.

If further experimentation is planned on this piece of equipment or similar apparatus, a protective enclosure as well as inert blanketing should be provided to insure the safety of the operator.

## RECOMMENDATIONS

Further study in the application of ultrasonic energy sources to chemical processes could prove to be quite rewarding. This thesis has presented the "how" but still leaves unanswered the "why" of separational improvement by the use of ultrasonic vibrations. Because the liquid and vapor in a small packed column are hard to observe (impossible when the column is thermally insulated), it is not certain which phase is more affected by the excitement of the ultrasonic vibrations. It may prove very interesting to use a glass bubble cap column with organic compound having color to visually observe the actual separation in the areas of the transducers.

Externally supplied ultrasonic energy can also be adapted to other chemical processes such as extraction and adsorption with a resulting increase in efficiency. The only foreseeable limitation on the use of ultrasonic energy would be the prohibitive consumption of power because of the low efficiency of conversion from electric to mechanical energy in large units.

# Table 26. Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| Meters | 39.370 | Inches |
| Meters | 2.281 | Feet |
| $Meters^2$ | 1550 | $Inches^2$ |
| $Meters^2$ | 10.76 | $Feet^2$ |
| $Centimeters^2$ | 0.1550 | $Inches^2$ |
| $Meters^3$ | 61,020 | $Inches^3$ |
| $Meters^3$ | 35.31 | $Feet^3$ |
| $Centimeters^3$ | 0.06102 | $Inches^3$ |
| $Feet^3$ | 1728 | $Inches^3$ |
| Newtons | $10^5$ | Dynes |
| Dynes | $1.020*10^{-6}$ | Kilogram |
| Kilogram | 2.205 | Pounds |
| Newtons | 0.2248 | Pounds |
| Grams | 0.03527 | Ounces |
| $Dynes/cm^2$ | 0.1 | $Newtons/m^2$ |
| $Dynes/cm^2$ | $1.450*10^{-5}$ | $Pounds/in^2$ |
| $Pounds/in^2$ | 6895 | $Newtons/m^2$ |
| $Grams/cm^3$ | 1000 | $Kilogram/m^3$ |
| $Pounds/in^3$ | 27,680 | $Kilogram/m^3$ |
| $Pounds/ft^3$ | 16.02 | $Kilogram/m^3$ |
| $Pounds/in^3$ | 27.68 | $Grams/cm^3$ |

## Symbol Designations

| Symbol | Description |
|---|---|
| $F_A$ | Separation Factor |
| $R_b$ | Refractive Index of the Bottom Liquid |
| $R_o$ | Refractive Index of the Overhead Vapor |
| $T_b$ | Temperature of the Reboiler |
| $T_o$ | Temperature of the Overhead Vapor |
| $X_A$ | Bottom Liquid Composition |
| $Y_A$ | Overhead Vapor Composition |
| V | Voltage |
| Q | Electrical Charge |
| C | Capacitance |
| F | Force |
| T,W,L&D | Dimensions: Thickness, Width, Length and Diameter |
| dT,dL&dD | Small Changes in Dimensions |
| $d_{33}$ | Direct Charge Coefficient |
| $d_{31}$ | Transverse Charge Coefficient |
| $d_{15}$ | Shear Charge Coefficient |
| $g_{33}$ | Direct Voltage Coefficient |
| $g_{31}$ | Transverse Voltage Coefficient |
| $g_{15}$ | Shear Voltage Coefficient |
| P | Direction of the Polar Axis |
| $k_{33}$ | Direct Electromechanical Coupling Coefficient |
| $k_{31}$ | Transverse Electromechanical Coupling Coefficient |
| $k_{15}$ | Shear Electromechanical Coupling Coefficient |

Symbol Designations - Cont'd

| Symbol | Description |
|---|---|
| $k_p$ | Planar Electromechanical Coupling Coefficient |
| $K_3$ | Relative Dielectric Constant Measured Along the Poling Axis |
| $K_1$ | Relative Dielectric Constant Measured at Right Angles to the Poling Axis |
| $Y_{ij}$ | Young's Modulus Measured at Constant Electric Field |
| $Q_m$ | Mechanical Q (Quality Factor) |
| $P_r$ | Remanent Polarization |
| $E_c$ | Coercive Field |
| $Z_m$ | Impedance at Resonance |
| $f_r$ | Resonance Frequency |
| P | Powerstat Reading |
| t | Time, Second |

## FOOTNOTES

(1) Foust, Alan S. et al, Principles of Unit Operations, New York: John Wiley & Sons, Inc., 1960, pp. 267-270.

(2) Chilton, T. H., and A. P. Colburn, Industrial and Engineering Chemistry, Vol. 27, No. 5, March 1935, pp. 255-260.

(3) Molokanov, Yu. M., Theoretical Foundations of Chemical Engineering, Vol. 1, No. 3, May-June 1967, pp. 261-266.

(4) Grinevich, A. T., Chemical and Petroleum Engineering, No. 2, February 1965, pp. 105-108.

(5) Silvery, F. C. and G. J. Keller, Chemical Engineering Progress, Vol. 62, No. 1, January 1966, pp. 68-74.

(6) Wall, K. J., Chemical and Process Engineering, Vol. 48, No. 7, July 1967, pp. 56-60.

(7) Mykolnikov, I. A. and L. S. Oshurkova, Coke and Chemistry, No. 3, 1964, pp. 51-52.

(8) Eckert, J. S. et al, Chemical Engineering Progress, Vol. 60, No. 10, October 1964, pp. 71-72.

(9) Morton, F. et al, Institute of Chemical Engineers - Transactions, Vol. 42, No. 1, 1964, pp. 35-43.

(10) Molyneux, F., Chemical and Process Engineering, Vol. 41, No. 2, February 1960, pp. 43-47.

(11) Blyakhman, L. I. and L. S. Davydov, Journal of Applied Chemistry (USSR), Vol. 41, No. 12, December 1968, pp. 2774-2777.

(12) Norman, W. S. et al, Industrial Chemist, Vol. 37, No. 2, February 1961, pp. 55-59.

(13) Samsel, R. W., Chemical Engineering Progress - Symposium Series, Vol. 47, No. 1, May 1950, pp. 77-81.

(14) Stokes, C. A. and J. E. Vivian, Chemical Engineering Progress - Symposium Series, Vol. 47, No. 1, May 1950, pp. 11-21.

(15) Koenig, W. Annals of Physics, Vol. 42, No. 353, 1891, p. 549.

(16) Kanser, H. W., Chemical Engineering, Vol. 57, No. 5, March 1950, pp. 158-163.

## FOOTNOTES - continued

(17) Sun, Shiou Chuam, Mining Engineering, 1951, pp. 865-867.

(18) Bretsznajder, S. et al, International Chemical Engineering, Vol. 3, No. 4, October 1963, pp. 496-502.

(19) Lesniewicz, L. et al, Chemical Stoichiometry, Vol. 3, 1958, p. 259.

(20) McKittrich, et al, U.S. Patent 2,265,762, December 9, 1941.

(21) Yasunago, T. et al, International Congress on Acoustics, Vol. 5, August 21-28, 1968, pp. 61-64.

(22) Lewis, M. F., Journal of Acoustical Society of America, Vol. 44, No. 3, September 1968, pp. 713-16

(23) McCarthy, W. S., Adhesives Age, Vol. 11, No. 7, July 1968, pp. 21-24.

(24) Tani, Y., Electronic & Communication in Japan, Vol. 48, No. 11, November 1965, pp. 192-198.

(25) Brewer, R. G., Applied Physics Letters, Vol. 6, No. 8, April 15, 1965, pp. 165-166.

(26) Neppiras, E. A., Ultrasonics, Vol. 3, January-March 1965, pp. 9-17.

## REFERENCES

Perry, J. H. et al, Chemical Engineers' Handbook, New York: McGraw-Hill Book Company, 1963.

Washburn, E. W. ed. et al, International Critical Tables of Numerical Data, Physics, Chemistry and Technology, New York: McGraw-Hill Book Company, 1926.

Weast, R. C., ed. et al, Handbook of Chemistry and Physics, 51st edition, Cleveland, Ohio: The Chemical Rubber Company, 1971.

Glennite Piezoceramics Catalog H-700, Gulton Industries, Inc., Fullerton, California, 1970.

Tower Packings, Bulletin TP-71, Norton Chemical Process Products Division, Akron, Ohio, 1971.

Design Information for Packed Towers, Bulletin DC-10R, Norton Chemical Process Products Division, Akron, Ohio, 1971.