

ABSTRACT

Gas-phase-controlled mass transfer for the vaporization of benzene into single bubbles of an inert carrier gas has been studied. The carrier gases used were helium, nitrogen and Freon-14. Mass transfer was measured by direct determination of the volume change as the bubble rose up the column. End-effect mass transfer was eliminated by forming the bubble under water and then allowing the bubble to rise. Average mass-transfer coefficients were calculated using an integrated form of equation. Unexpected dynamic effects prevented the evaluation of mass-transfer coefficients other than at points close to the benzene-water interface. A high speed camera was used to take photographs of the rising bubble in order to determine bubble rise velocity and shape factors. The bubbles were found to assume a spherical cap shape with a constant eccentricity of 3.5 for all three carrier gases. The experimental volume range varied from 1.7 to 2.4 cm equivalent spherical diameter. The bubble rise velocity for all three carrier gases was found to be a linear function of bubble volume.

Mass-transfer coefficients were observed to decrease with bubble volume for all three systems, particularly for Freon-14. The average values for the gas-phase mass-transfer coefficients were 1.99×10^{-5} , 1.90×10^{-5} and 1.09×10^{-5} g.moles/cm² sec atm for helium, nitrogen and Freon-14 carrier

gases respectively. The direction of the variation of K_G was in accordance with the change of diffusivity of benzene in the carrier gases but critical examination of the data showed that the magnitude of the K_G values was in error. The values were low indicating that the initial volume measurements were smaller than the true values due to inertia effects in the direct volume measurement apparatus. It was concluded that the direct volume measurement method was not a suitable method for measuring mass transfer coefficients when mass-transfer rates are high.

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NOMENCLATURE

a	:	width of spherical cap bubble (cm)
a_s	:	semi-width of spherical cap bubble (cm)
A	:	surface area (cm ²)
A_F	:	frontal surface area of spherical cap bubble (cm ²)
b	:	height of spherical cap bubble (cm)
D_{AB}	:	diffusivity (cm ² /sec)
de	:	equivalent spherical diameter (cm)
e_{AB}	:	energy of molecular interaction (ergs)
E	:	eccentricity of spherical cap bubble
g	:	local acceleration due to gravity (980.6 cm/sec ²)
ξ_0	:	dimensional constant (1.01325 x 10 ⁶ dynes/cm ² atm)
H	:	distance of reference level in column below datum line (cm)
ΔHg	:	mercury travel in glass capillary (cm)
k	:	Boltzmann's constant
K_G	:	average gas-phase mass-transfer coefficient (g.moles/cm ² sec atm)
M_A, M_B	:	molecular weight of components A and B
ΔmV	:	voltage drop across platinum wire (millivolts)
N	:	number of moles transferred (g.moles)
p^*	:	partial pressure of transferring component at gas-liquid interface (atm)
p^0	:	vapor pressure of volatile component (atm)
p_b	:	partial pressure of volatile component in bulk of gas phase (atm)
P	:	total pressure (atm)

(x)

PATM, P_t : atmospheric pressure (cm Hg, atm)
R : ideal gas constant (82.06 atm cc/g.mole $^{\circ}$ K)
r : radius of circle containing spherical cap
 r_{AB} : molecular separation at collision (\AA)
 S_x : surface area
T : absolute temperature ($^{\circ}$ K)
 T_b : normal boiling point ($^{\circ}$ K)
 \bar{U} : average velocity of bubble (cm/sec)
V : volume of bubble (cc)
 \bar{V} : average volume of bubble over interval (cc)
 ΔV : volume change of bubble after release (cc)
v : molecular volume
xAREA : effective cross-sectional area of glass capillary (cm^2)
y : mole fraction of volatile component
z : distance of reference level from datum line (cm)
 ρ_B : density of benzene (g/ml)
 ρ_M : density of mercury (g/ml)
 ρ_W : density of water (g/ml)
 θ : time (sec)
 ϕ : angle

Subscripts

1 position of inverting spoon
o,1 position of interface
2 6 inches above interface
3 12 inches above interface
4 24 inches above interface
5 top of column

I. INTRODUCTION

The majority of industrial mass-transfer operations involve the contacting of liquids and gases in froths and foams as, for example, on a sieve plate in a distillation column. In an effort to simplify and eliminate many of the operational variables associated with pilot plant or industrial sized equipment, mass-transfer studies have been carried out in the expectation that the knowledge gained from the investigations could be applied to large scale mass-transfer operations. However, the rising bubble studies which were carried out under gas-phase-controlled conditions, have not been particularly successful. This has been attributed to end effect mass transfer taking place on bubble formation. As an alternative to studying mass transfer in streams of rising bubbles, investigations have been carried out under the conditions when a single bubble rises through a stagnant liquid. Investigators have used different methods for the evaluation of the volume change and computation of point and average mass-transfer coefficients. This work was undertaken to examine the applicability of these methods which were developed for studying liquid-phase-controlled mass transfer.

II. PREVIOUS WORK

Investigators have used different methods to measure the mass transfer taking place from a single bubble rising through a stagnant column of liquid. The methods are;

- (i) Direct measurement of bubble volume change
- (ii) Photographic methods
- (iii) Pressure measurement methods

(i) Volume Measurement Method

The volume measurement method was originally developed by Ledig and Weaver (1). A column of liquid was connected to a glass capillary through a mercury reservoir which provided the only opening to the atmosphere. When a bubble of gas was released into the column, direct volume measurements were made by shadowgraphs of the mercury travel within the glass capillary. The volume measurement apparatus has since been modified by Leonard and Houghton (2) and Johnson, Besik and Hamielec (3). Instead of taking shadowgraphs, a platinum wire was stretched within the glass capillary. By applying a current through the wire, the mercury movement was measured by noting the changing voltage drop across the wire. Photographs were taken to determine bubble shapes from which the surface area of the bubble was calculated. Two different types of equations have been developed for the evaluation of mass-transfer coefficients; a differential form and an integrated form of equation. Use of the differential form

of the equation involves the calculation of slopes from volume-time and pressure-depth relationships. The mass-transfer coefficient evaluated from the differential form of the equation is considered to be the instantaneous mass-transfer coefficient. Use of the integrated form of the equation involved the measurement of bubble volumes over a finite pool depth, when an average mass-transfer coefficient was computed. Leonard and Houghton (2) evaluated instantaneous mass-transfer coefficients for nitrous oxide-water and ethylene-water systems. They concluded that trace impurities in the water played a large role in the absorption rates through surface effects. Johnson, Besik and Hamielec (3) evaluated average mass-transfer coefficients for carbon dioxide-water, ethylene-water and butene-water systems. They experimented with a bubble volume range from 0.4 to 2.0 cm equivalent spherical diameter.

(ii) Photographic Methods

This method has been used by several investigators when the change in bubble volume was measured from photographs of the bubble as it rose up the column (4)(5). Garbarini and Chi Tien (4) measured instantaneous mass-transfer coefficients for a carbon dioxide-distilled water system. Two zoom lens movie cameras were used operating at right angles to each other in the same plane. The two cameras were mounted on a movable platform which was raised manually to follow the rising bubble. The volume ranges studied varied from 0.30 to 0.60 cm equivalent spherical diameter. Baird and Davidson (5)

measured mass-transfer coefficients for the carbon dioxide-water system over a volume range from 0.8 to 4.2 cm in diameter. Bubble volumes and surface areas were calculated from assumed shapes and measurements taken from the photographs.

(iii) Pressure Measurement Method

The pressure measurement method was developed by Calderbank and Lochiel (6) and has been used by Garbarini and Chi Tien (4), for the study of carbon dioxide-water systems. The method involved the measurement of pressure changes within a dead air space at the top of the column of liquid. The pressure changes within the dead air space were caused by the introduction of a bubble into the column and the subsequent volume change as the bubble rose through the liquid. Instantaneous mass-transfer coefficients were evaluated from pressure-time relationships. The surface area of the bubble was calculated from shape considerations and bubble dimensions taken from photographs of the rising bubble.

The three different methods have not given consistent results. For the same system, there has been fairly good agreement between investigators using the same methods (2)(3). There is considerable scatter in mass-transfer coefficient data due to the evaluation of surface areas from photographs. The different methods have errors associated with them which would account for some of the reported differences (4). For the volume measurement method, the mercury in the glass capillary is unable to keep pace with the actual bubble volume change at high mass-transfer rates. This has been attributed

to the relatively high viscosity of mercury. The pressure measurement method avoids the problem of the dynamic lag at high mass-transfer rates but Baird (7) has noted that the non-isothermal nature of the dead air space might have to be taken into account when calculating mass-transfer coefficients. Furthermore, some difficulty has been reported in recording the initial pressure difference when bubble volumes are small. (4). The photographic method is subject to criticism since bubble volumes are determined from projected bubble cross-sections and assumed bubble shapes and is therefore not a direct measurement of bubble volume as with the volume and pressure methods.

Deviations from rectilinear motion and bubble instability over certain volume ranges are largely responsible for errors involved in the determination of the bubble surface area.

III. THEORETICAL

1. Equation for the evaluation of K_G

The rate of mass transfer for a pure liquid evaporating into an inert carrier gas is given by;

$$\frac{dn}{d\theta} = K_G A (p^* - p_b) \quad (1.1)$$

where; $\frac{dn}{d\theta}$ = number of g.moles transferred per unit of time (g.moles/sec)

A = surface area available for mass transfer (cm²)

p^* = partial pressure of the volatile components at the gas-liquid interface (atm) and is assumed to be equal to the pure liquid vapor pressure p^0 (atm)

p_b = partial pressure of the volatile component in the bulk of the gas phase (atm)

K_G = gas-phase mass-transfer coefficient (g.moles/cm² atm sec)

In order to experimentally measure the gas-phase mass-transfer coefficient, the mass-transfer rate ($dn/d\theta$) and the partial pressure driving force ($p^* - p_b$) had to be expressed in terms of measurable variables. An integrated form of equation was derived for use in conjunction with the volume measurement method for a two-phase system consisting of benzene and water. The volume measurement method was considered to be the most suitable method for determining the volume changes taking place for the experimental gas-phase-controlled system.

The partial pressure driving force ($p^* - p_b$) was expressed in terms of the vapor pressure of the liquid (p^0), the total

pressure within the bubble (P) and the mole fraction of the volatile component within the bulk phase of the bubble (y).

$$(p^* - p_b) = (p^0 - yP) \tag{1.2}$$

It was assumed that the bulk of the gas was perfectly mixed. Furthermore, assuming isothermal conditions within the bubble, the mole fraction (y) could be expressed in terms of the ideal gas law to give;

$$(p^0 - yP) = (p^0 - P + \frac{P_0 V_0}{V}) \tag{1.3}$$

where; P_0 = pressure at benzene-water interface (atm)
 V_0 = volume of bubble at benzene-water interface (cc)
 V = volume of bubble within the benzene phase (cc)

$$y = \frac{PV - P_0 V_0}{PV} \tag{1.4}$$

Hence, the partial pressure driving force has been expressed in terms of the measurable variables p^0, P, P_0, V_0 and V .

For the assumption of isothermal conditions within the bubble, the mass-transfer rate ($dn/d\theta$) was expressed in terms of the ideal gas law which was differentiated to give;

$$\frac{dn}{d\theta} = \frac{1}{RT} \left(P \frac{dV}{d\theta} + V \frac{dP}{d\theta} \right) \tag{1.5}$$

From the relationship expressing hydrostatic pressure as a function of liquid depth;

$$P = \rho \frac{g}{g_0} H \quad (1.6)$$

where; P = hydrostatic pressure (atm)
 ρ = density of liquid (g/ml)
 H = depth in liquid (cm)
 g = local acceleration due to gravity
 (980.6 cm/sec²)
 g_0 = dimensional constant (1.01325 x 10⁶ dynes/cm² atm)

The rising velocity of the bubble was expressed as;

$$U = -\frac{dH}{d\theta} = -\frac{g_0}{\rho g} \frac{dP}{d\theta} \quad (1.7)$$

and from the chain rule;

$$\frac{dP}{d\theta} = \frac{dV}{d\theta} \frac{dP}{dV} \quad (1.8)$$

solving for (dP/dθ) in equation (1.7) and for (dV/dθ) in equations (1.7) and (1.8);

$$\frac{dP}{d\theta} = -U\rho g \frac{g_0}{g} \quad (1.9)$$

$$\frac{dV}{d\theta} = -U\rho g \frac{dV}{g_0 dP} \quad (1.10)$$

substituting for (dP/dθ) and (dV/dθ) from equations (1.9) and (1.10) into equation (1.5);

$$\frac{dn}{d\theta} = \frac{-U\rho g}{RTg_0} \left(P \frac{dV}{dP} + V \right) \quad (1.11)$$

equating (1.11) and (1.3);

$$\frac{-U_0 g}{RT g_0} \cdot \left(P \frac{dV}{dP} + V \right) = K_G A (p^0 - P + \frac{P_0 V_0}{V}) \quad (1.12)$$

re-arranging and multiplying equation (1.12) by dP and

$$\frac{-g_0 RT}{U_0 \rho g} ;$$

$$PdV + VdP = \frac{-g_0 RT K_G A}{U_0 \rho g} (p^0 - P + \frac{P_0 V_0}{V}) dP \quad (1.13)$$

Integrating equation (1.13) from position 1 to position 2 over a small interval and noting that the integral

$$P_0 V_0 \int_1^2 \frac{dP}{V}$$

was approximated by the trapezoidal rule;

$$K_G = \frac{2.0 \bar{U} \rho}{1033.23 RTA} \frac{P_2 V_2 - P_1 V_1}{(P_1 - P_2) (2p^0 + \frac{P_0 V_0 (V_2 + V_1)}{V_1 V_2}) - (P_1 + P_2)} \quad (1.15)$$

where; K_G = average gas-phase mass-transfer coefficient (g.moles/cm² sec atm)

\bar{U} = average velocity of bubble over interval (cm/sec)

ρ = density of pure liquid (g/ml)

$\frac{g}{g_0}$ = 1/1033.23 (cm/sec²)/(dynes/cm² atm)

g_0

R = ideal gas constant (82.06 atm cc/g.mole °K)

T = absolute temperature (°K)

A = surface area available for mass transfer (cm²)

P_1, P_2 = pressure (atm)

V_1, V_2 = volume of bubble (cc)

P_0, V_0 = pressure and volume of bubble at benzene-water interface (atm, cc)

p^0 = vapor pressure of pure liquid (atm)

The equation (1.15) for K_G is derived rigorously in appendix 3.1. The following assumptions were used in the derivation of equation (1.15);

- (i) Isothermal conditions within the bubble
- (ii) Perfect mixing within the bulk of the carrier gas
- (iii) Water vapor in the carrier gas is considered inert and therefore has no effect on subsequent mass transfer in the benzene phase

2. Frontal surface area of a spherical cap bubble

In reference to figure 1a, the volume of a spherical cap bubble may be determined in terms of the radius of the sphere of which it is part of and the angle ϑ ;

$$V = \frac{\pi r^3}{3} (2 + \cos^3 \vartheta - 3 \cos \vartheta) \quad (2.1)$$

The frontal surface area of the spherical cap bubble is given by;

$$A_F = 2\pi r^2 (1 - \cos \vartheta) \quad (2.2)$$

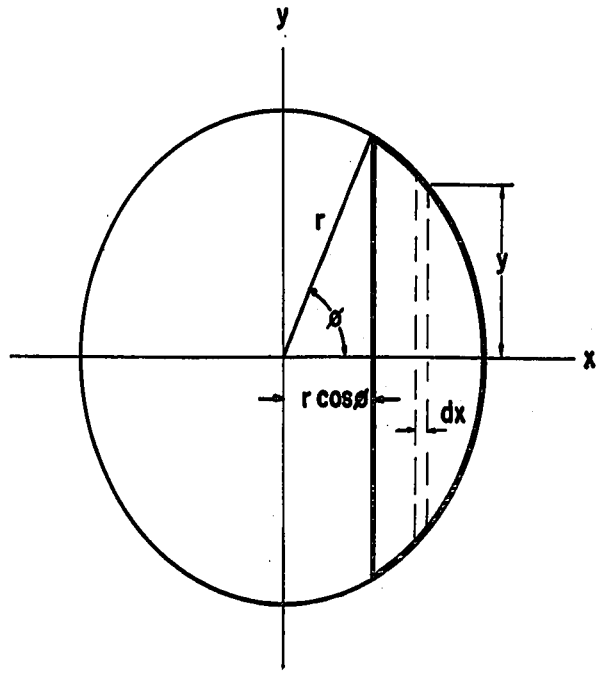


Figure 1a

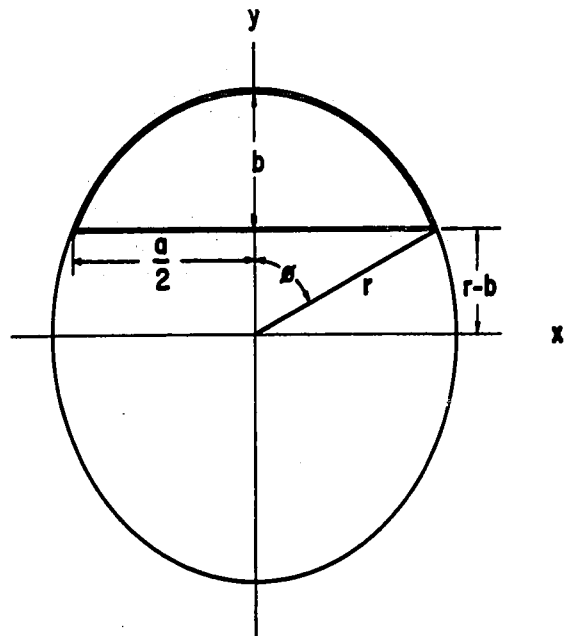


Figure 1b

solving for r in equation (2.1) and substituting the result in equation (2.2), we have;

$$A_F = \frac{2\pi(1-\cos\phi)}{\left(\pi\left(\frac{2}{3} - \cos\phi + \frac{\cos^3\phi}{3}\right)\right)^{2/3}} V^{2/3} \quad (2.3)$$

With reference to figure 1b, the cosine of the angle ϕ may be expressed in terms of the eccentricity of the spherical cap bubble which is defined as its width to height ratio;

$$\cos\phi = \frac{E^2-4}{E^2+4} \quad (2.4)$$

substituting equation (2.4) in (2.3) and simplifying;

$$A_F = \frac{\pi(E^2 + 4)}{\left(\left(\frac{\pi}{3}\right)(3E^2 + 4)\right)^{2/3}} V^{2/3} \quad (2.5)$$

where; A_F = frontal surface area of spherical cap bubble (cm²)
 V = volume of bubble (cc)
 E = eccentricity = width to height ratio of bubble

Equation (2.5) is derived rigorously in appendix 3.2.

3. Volume of bubble from photography

With reference to figure 1b, the volume of a solid of revolution gives;

$$V = \pi \int_{r-b}^r y^2 dx \quad (3.1)$$

so that;

$$V = \pi (rb^2 - \frac{b^3}{3}) \quad (3.2)$$

from appendix 3.2, equation (2.18);

$$r = \frac{4b^2 + a^2}{8b} \quad (3.3)$$

substituting equation (3.3) into (3.2) and simplifying;

$$V = \frac{\pi a^3}{24E} \cdot (3 + \frac{4}{E^2}) \quad (3.4)$$

or,
$$V = \frac{\pi a_s^3}{3E} \cdot (3 + \frac{4}{E^2}) \quad (3.5)$$

- where;
- V = volume of bubble (cc)
 - a = width of bubble (cm)
 - a_s = semi-width of bubble (cm)
 - E = eccentricity of bubble

Equation (3.5) is derived rigorously in appendix 3.3.

IV. EXPERIMENTAL

1. Experimental Method

In reviewing the advantages and disadvantages of the available methods, it was decided that the volume measurement method could best be adapted to a gas-phase-controlled system. The volume changes of the bubble were expected to be small in comparison with those of the liquid-phase studies when a considerable proportion of the gas bubble was allowed to dissolve. Consequently, no dynamic lag from mercury travel in the glass capillary was anticipated. The photographic method was eliminated since it was felt that the small volume changes expected could not be determined from photographs. The pressure measurement method was not chosen due to the unsettled question of the isothermal/non-isothermal nature of the dead air space. It was felt that the equations for the calculation of mass-transfer coefficients would become complex if the thermal history of the dead air space had to be taken into account.

Initially, a nitrogen-water system was investigated where a bubble was formed under mercury and released into the water phase. There was an oscillation of the bubble as it rose through the mercury-water interface which prevented the evaluation of mass-transfer coefficients. At the same time, it was felt that the volatility of water was rather low. A search was then made for a two-phase system consisting of an upper phase of relatively high volatility for which average mass-transfer coefficients could be evaluated and a lower

phase of comparable density and low volatility which would serve as a forming and calming medium. Benzene and water were selected as the upper and lower phases respectively and average mass-transfer coefficients were evaluated for nitrogen-benzene, helium-benzene and Freon-14-benzene systems respectively. It was assumed that the gas bubble would be saturated with water as it entered the benzene phase and that the water vapor would act as part of the inert carrier gas.

2. Apparatus

A schematic diagram of the equipment is shown in figure 2, and full equipment details are given in appendix 6. The apparatus consists of three basic units;

(a) Carrier gas supply, flow regulation and bubble formation equipment

(b) Mass-transfer column

(c) Volume measurement equipment

and (d) Photographic equipment

(a) Carrier gas supply, flow regulation and bubble formation equipment

Flow of carrier gas from the cylinder (10) was regulated through a flow controller and gas regulator (11). The carrier gas was then passed through a drying column (12) to remove any moisture which may have been present. The gas was passed through valve (1) and the amount of gas admitted to the column was controlled by means of a needle valve (2). Valve (3) was used as a back-pressure relief valve. A check valve (14) prevented liquid in the column from entering the gas line. The bubble retainer (15) was made out of a section of stainless steel pipe which contained a stainless steel spoon (13). The carrier gas was injected into the retainer and was trapped by the inverted spoon. To release the gas bubble into the column of liquid, the spoon was simply rotated through 180 degrees. Details of the retainer are shown in figure 3.

(b) Mass-transfer column

The column was made up of three sections of Q.V.F. glass

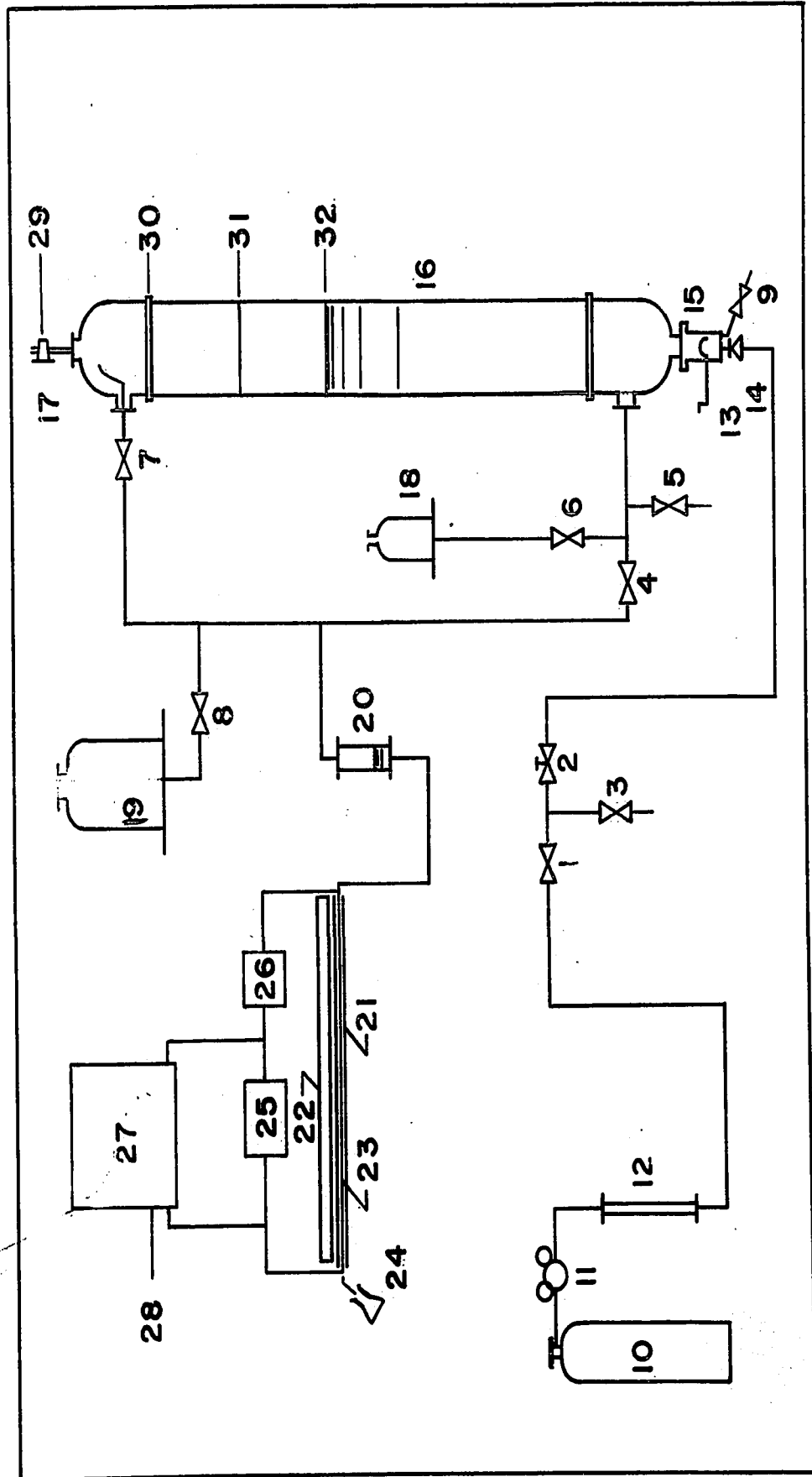


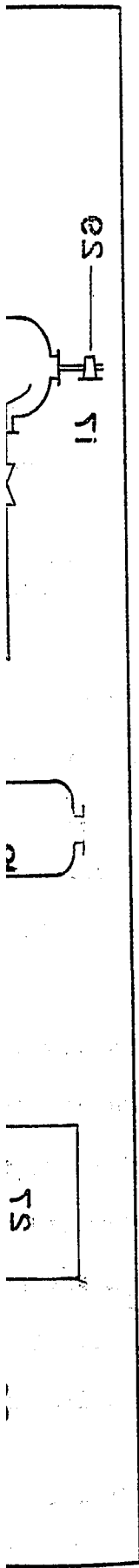
Figure 2

EQUIPMENT LIST

(figure 2)

1. on-off valve (main carrier gas line)
2. needle valve (flow control to bubble retainer)
3. on-off valve (vent to atmosphere)
4. ball valve (column to mercury reservoir)
5. ball valve (column water drain)
6. ball valve (water reservoir to column)
7. ball valve (column to mercury reservoir)
8. needle valve (benzene reservoir to column)
9. needle valve (bubble retainer drain)

10. carrier gas cylinder
11. gas regulator
12. drying column
13. inverting spoon
14. stainless steel check valve
15. stainless steel bubble retainer
16. Q.V.F. glass column
17. Teflon stopcock
18. water reservoir
19. benzene reservoir
20. mercury reservoir
21. glass capillary (0.1210 inch I.D.)
22. calibrated metal scale (in cm)
23. platinum wire (0.01 inch dia.)
24. mercury trap
28. remote event marker actuator lead
25. dc constant current supply
26. VTVM (vacuum tube voltmeter)
27. chart recorder
29. datum level $z=0$
30. reference $z=38.3$ cm
31. reference $z=69.0$ cm
32. reference $z=99.7$ cm



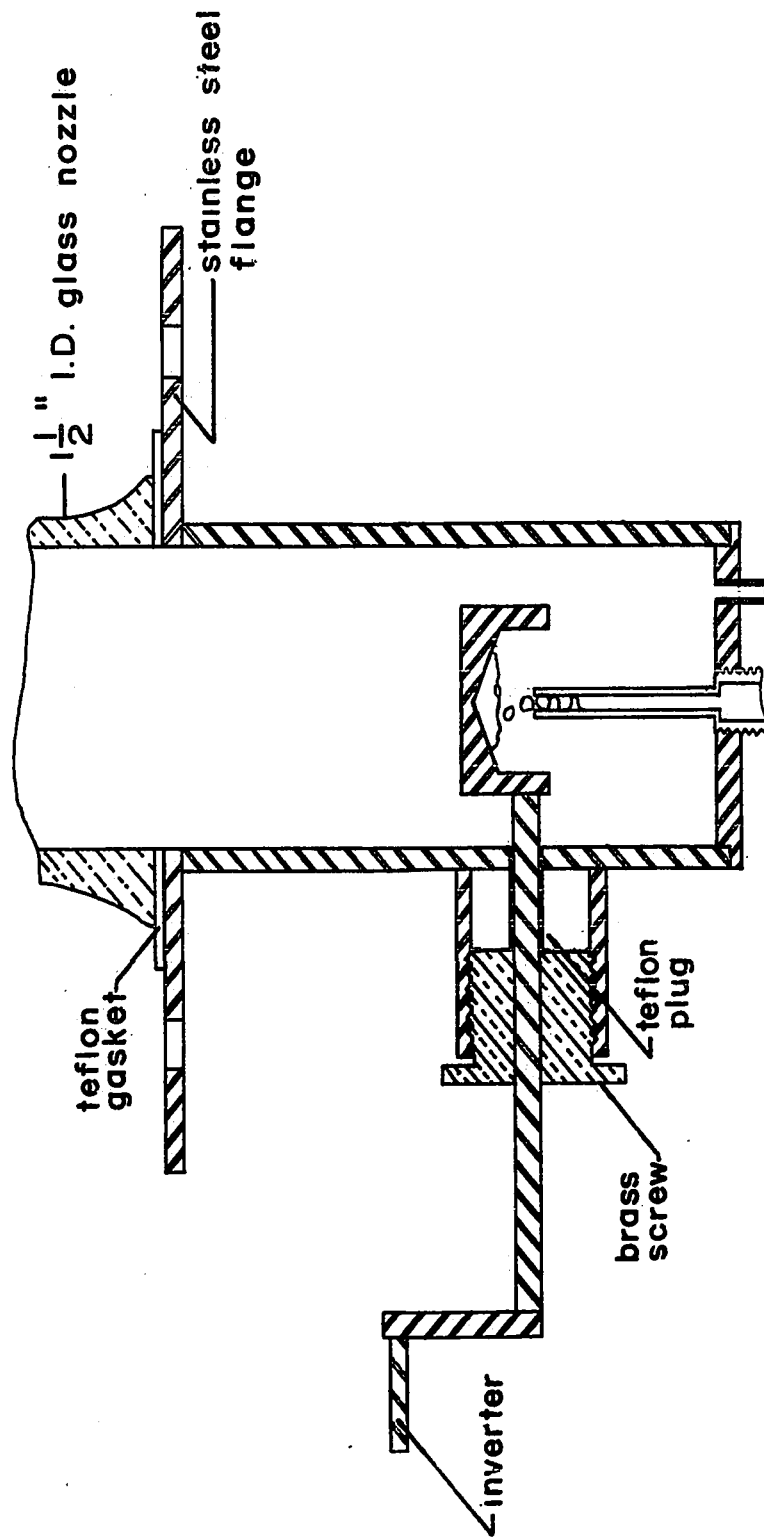


Figure 3

consisting of two column adaptors and one five foot section of six inch I.D. standard precision bore pipe. The sections were connected by backing flanges and sealed with compressed asbestos fibre gaskets in the upper part of the column containing benzene and neoprene rubber gaskets in the lower part of the column containing water. A Teflon gasket was used to connect the bubble retainer to the bottom column adaptor. The column (16) was connected to the mercury reservoir (20) through the horizontal nozzles of the column adaptors. Valves (4) and (7) were used to separate the column from the mercury reservoir if so desired. Bubbles of gas were removed from the column through the stopcock connected to the vertical nozzle of the top column adaptor. Water was removed from the column through valve (5) or added from the water reservoir (18) by gravity feed through valve (6). Benzene was added to the column from a reservoir (19) by gravity feed through valves (7) and (8).

(c) Volume measurement apparatus

The volume measurement apparatus consisted of a length of precision bore glass capillary tubing, a platinum wire, a two pen chart recorder, a DC current supply, a vacuum tube voltmeter (VTVM) and a mercury reservoir.

(i) Mercury reservoir

The mercury reservoir (20) consisted of a 12 inch length of one inch I.D. Q.V.F. standard precision bore glass pipe. The ends of the pipe were sealed by two brass flanges containing Teflon gaskets. The lower flange in contact with

glass nozzle
1.0 I.D.
1.0"
Teflon
5 feet

mercury was coated with a Teflon spray. The upper brass flange contained a drilled out compression fitting so that a section of one-quarter inch copper tubing would slide freely through it. The tubing was sealed by means of two rubber O-rings which were held in place by a pipe cap. The bottom of the mercury reservoir was connected to the glass capillary (21) by means of a length of flexible pneumatic tubing. Further details of the mercury reservoir and its lift device are given in figure 4.

(ii) Precision bore glass capillary and platform

The pneumatic tubing from the mercury reservoir (20) was connected to a 33 inch length of 0.1210 inch I.D. precision bore capillary (21) by means of a plexiglass fitting. The fitting also contained an insulating post as shown in figure 5. The plexiglass fitting was made up of two separate sections so that it could be taken apart in order to periodically clean the glass capillary. The glass capillary was supported by a wooden platform which could be leveled by means of three threaded support rods. A calibrated scale (in cm) (22) was fitted next to the capillary (21) and equipped with a slide which was used to determine the initial volume of the bubble injected into the bubble retainer (15). A 0.01 inch diameter platinum wire (23) was stretched within the glass capillary and connected to the insulating post at one end of the platform and to an alligator clip at the other end of the platform. The open end of the glass capillary was connected to a mercury trap (24) by means of a small plexiglass fitting.

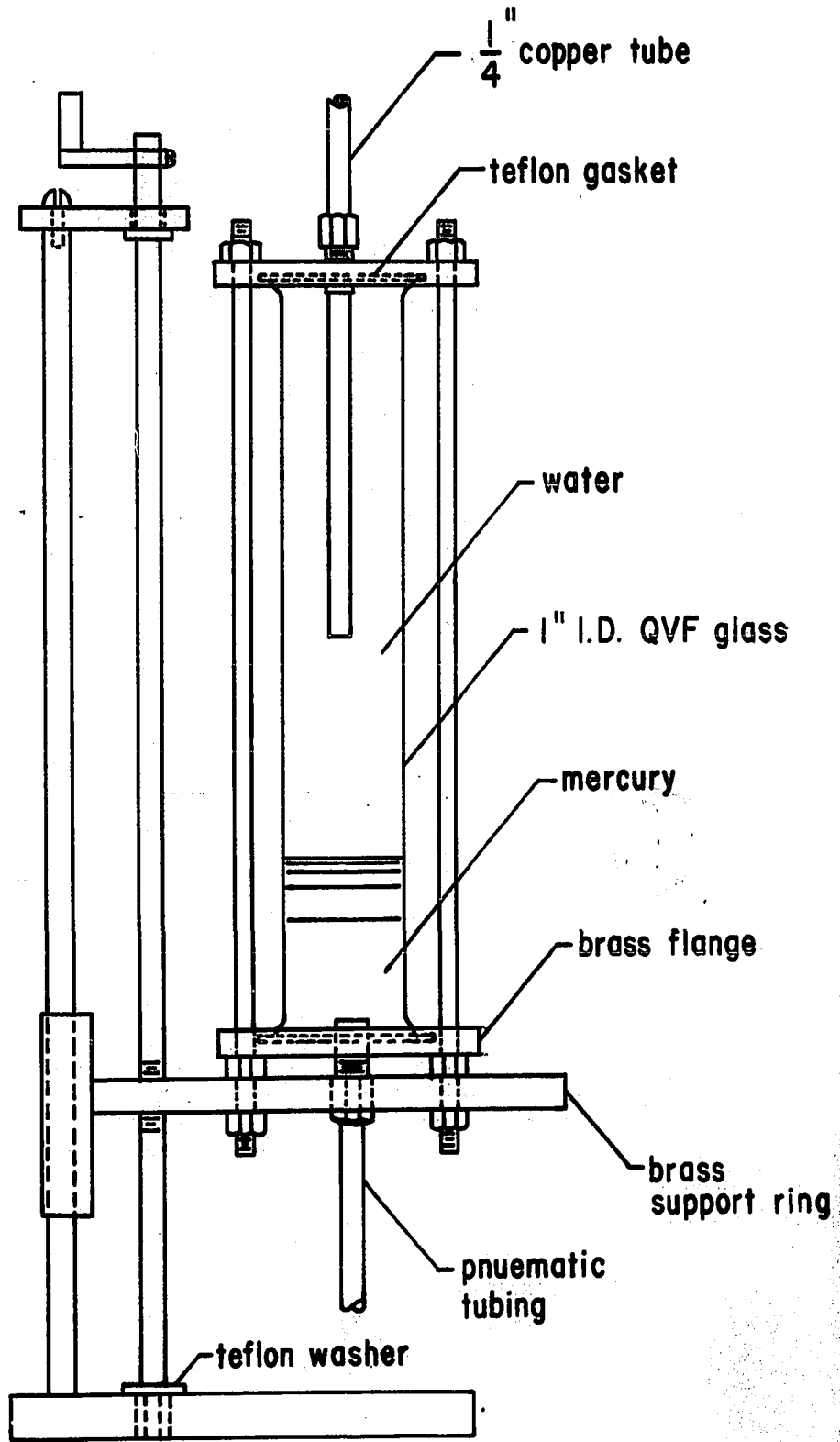


Figure 4

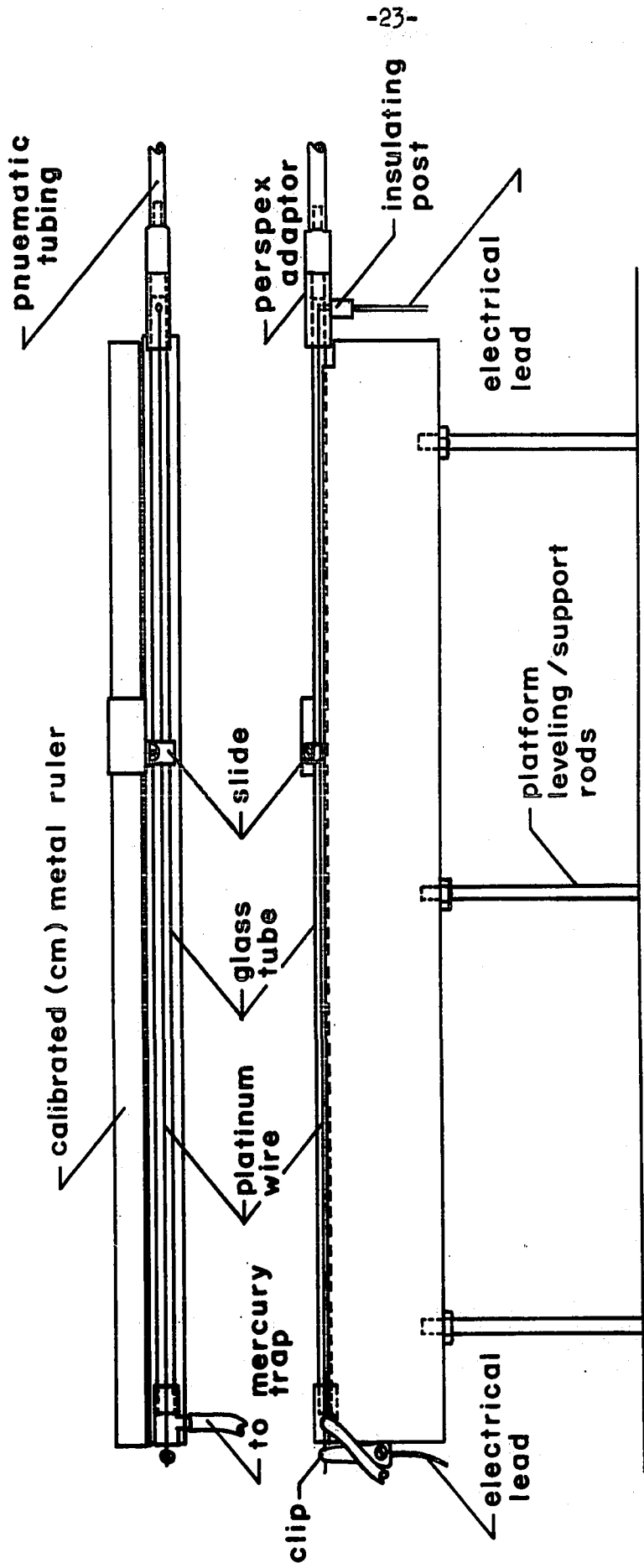
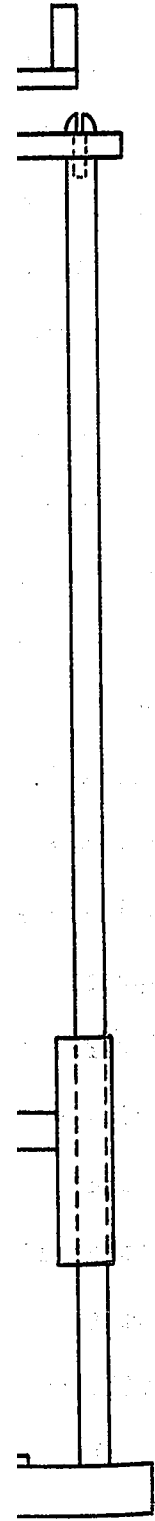


Figure 5

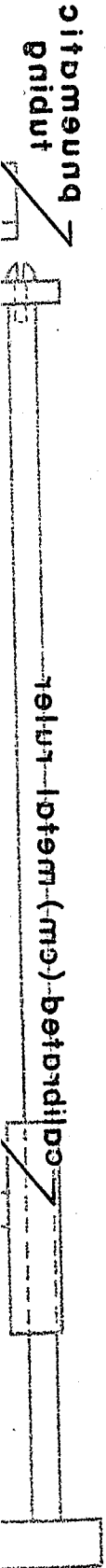
(iii) Recorder, DC current supply and vacuum tube voltmeter

The DC constant current supply (25) and the VTVM (26) were connected in series so that the VTVM could monitor the current from the current supply. The chart recorder (27) was set to record the voltage drop across the platinum wire (23) and was therefore wired in parallel with the constant current supply (25). The supply was connected to the insulating post and alligator clip at both ends of the wooden support platform.

A photograph of the experimental apparatus is shown in figure 6.

(d) Photographic equipment

Bubble surface areas and rise velocities were determined using a HYCAM high speed camera. The camera had a maximum frame rate of 18,000 frames/sec for 1/2 frame 16 mm film. The camera was fitted with a timing light generator which enabled accurate evaluation of rise velocities. In order to reduce image distortion, a polished perspex block, 5 cm by 11 cm was made and fitted to the column. Clear calibrated tape (in cm) was placed both vertically and horizontally on the block. A different number was placed on the block for each photographic run for ease of identification. A schematic layout of the photographic equipment is shown in figure 7 and full details are given in appendix 9.



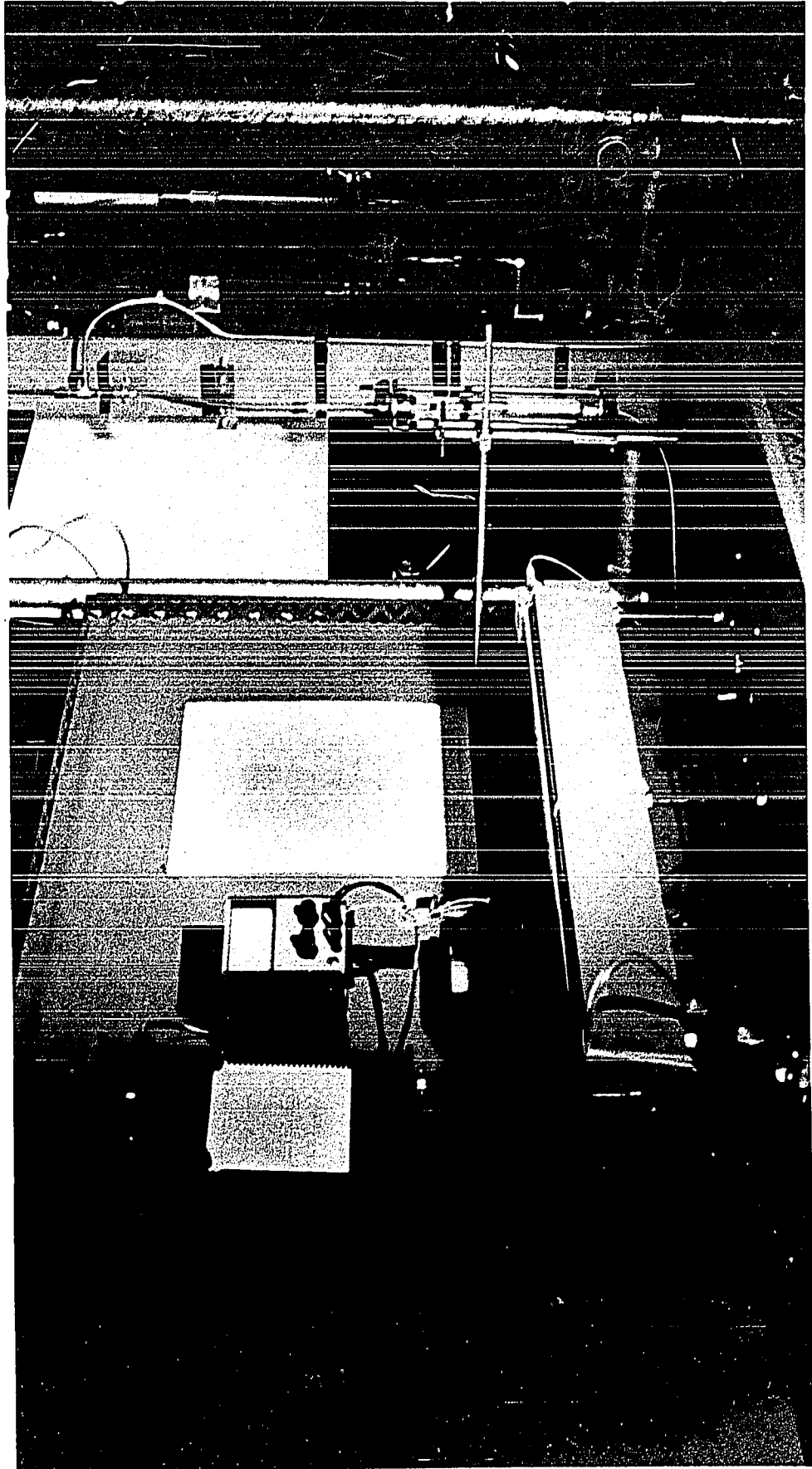


FIGURE 6

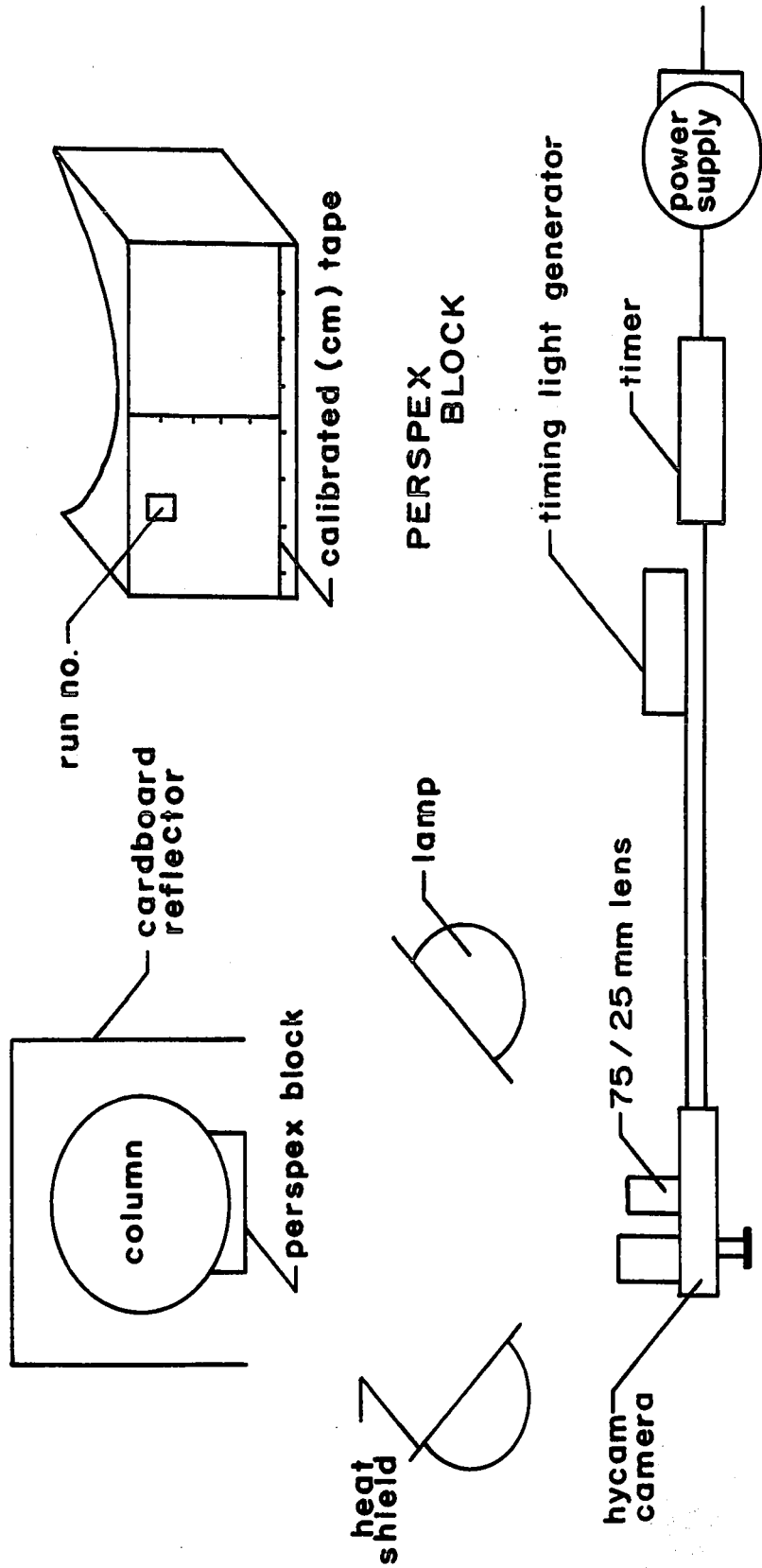


Figure 7

3. Experimental procedure

The column was first completely filled with water and benzene. The water level was established after several runs to be at a point 99.7 cm below the centerline of the vent stopcock (17) located at the top of the column. The liquid phases were saturated with carrier gas by bubbling the gas through the column of liquid for approximately thirty minutes. To begin a run, the recorder, DC current supply and vacuum tube voltmeter were turned on and allowed to warm up for at least one hour. The chart speed of the recorder was set for 20 inches per minute and the input for a 1.0 millivolt full scale deflection. The power supply was set at 2.0 milliamps and was accurately monitored by the vacuum tube voltmeter. The carrier gas pressure was adjusted to about 5 psig. The position of the mercury reservoir was adjusted until the mercury just entered one end of the glass capillary. At this time, the benzene level in the column was checked and adjusted to maintain its level just above the centerline of the vent stopcock (17). The mercury reservoir was re-adjusted until the level of the benzene and the position of the mercury in the capillary were satisfactory. The stopcock was then closed and the initial position of the mercury in the capillary was noted and marked by means of the slide attached to the calibrated scale (22). The inverted spoon at the bottom of the column was then correctly positioned to receive the carrier gas which was admitted into the column through the needle valve (2). After the desired volume of gas had been introduced under the spoon, valve (2) was closed and

valve (3) opened to relieve the back-pressure in the carrier gas line. The slide device was moved to the new position of the mercury in the glass capillary and its position noted. The volume of the injected carrier gas was then determined from the difference between the initial and final positions of the slide. The recorder chart was activated and the recording pen was adjusted to give a good trace by placing it close to the chart margin. The bubble was then released by rotating the spoon. The volume change of the bubble was continuously recorded and reference points were noted by actuation of the remote event marker switch at the following levels in the column; 220 cm, 99.7 cm (interface), 69.0 cm, 38.3 cm, 19.0cm and 6.0 cm. The centerline of the vent stopcock (17) was taken as datum and the distances refer to points in the column below the stopcock. Some data for the nitrogen-benzene system were recorded at slightly different reference levels. The reference levels for runs N001 to N056 are given in appendix 1. The chart on the recorder was then stopped and placed in a standby mode. The mercury in the glass capillary was drawn back to the mercury reservoir by draining some water from the column through valve (5). The vent stopcock at the top of the column was then slowly opened to prevent a mercury surge in the capillary. Atmospheric pressure and column temperature were noted. The temperature of the liquid in the column was determined from a sample of water taken from the column through valve (5). The procedure was then repeated with several runs being carried out on any one day.

The following procedure was used for taking photographs of the rising bubble. The timing light generator was set to its maximum value of 1000 cycles per second and the 'powerstat' to fifty-five volts. At fifty-five volts, calibration curves supplied with the camera indicated an approximate frame rate of 4000 pictures per second (for 16 mm film). A bubble was then formed under the inverter at the bottom of the column. A timer in the line between the variable 'powerstat' and the camera was set to shut off the camera motor after approximately two seconds of operation. The two Colortran lamps were then turned on. The lamps were supplied with heat absorption shields to reduce the amount of infra-red radiation striking the glass column. The bubble was released and the camera activated when the bubble was approximately six inches below the perspex block. The procedure was then repeated for successive photographic runs. With the 75 mm Comiscar lens, photographs were taken primarily at a point six inches above the interface, although some were taken at the interface. With the 25 mm Comiscar lens, photographs were taken over the first foot of column above and including the interface.

V. RESULTS

Examination of recorder volume trace

Examination of the volume-time trace on the recorder indicated that there was an unexpected lag between the actuation of the event marker and the mercury movement within the capillary. If unaccounted for, the lag would introduce errors in the evaluation of mass-transfer coefficients through miss-matching of the volume of the bubble with a reference level in the column. Three methods were used to evaluate the lag;

- (1) Visual inspection of the recorder trace indicated the position of the interface. When the bubble passed through the interface, the slope of the volume trace grew abruptly steeper as shown in figure 8.
- (2) The position of the interface was back-calculated from the assumption that the bubble was saturated with water vapor at the interface.
- (3) Difference between first movement of mercury in the capillary and actuation of the event marker on bubble release.

From visual inspection of the recorder volume trace for several runs, the lag was found to remain relatively constant. When the position of the interface was found to be indistinct due to bubble instability or oscillation, methods (2) or (3) were used to determine the lag. Interface positions determined from the three methods are compared in appendix 5 for several nitrogen mass-transfer runs.

A further dynamic effect was noted for some mass-transfer

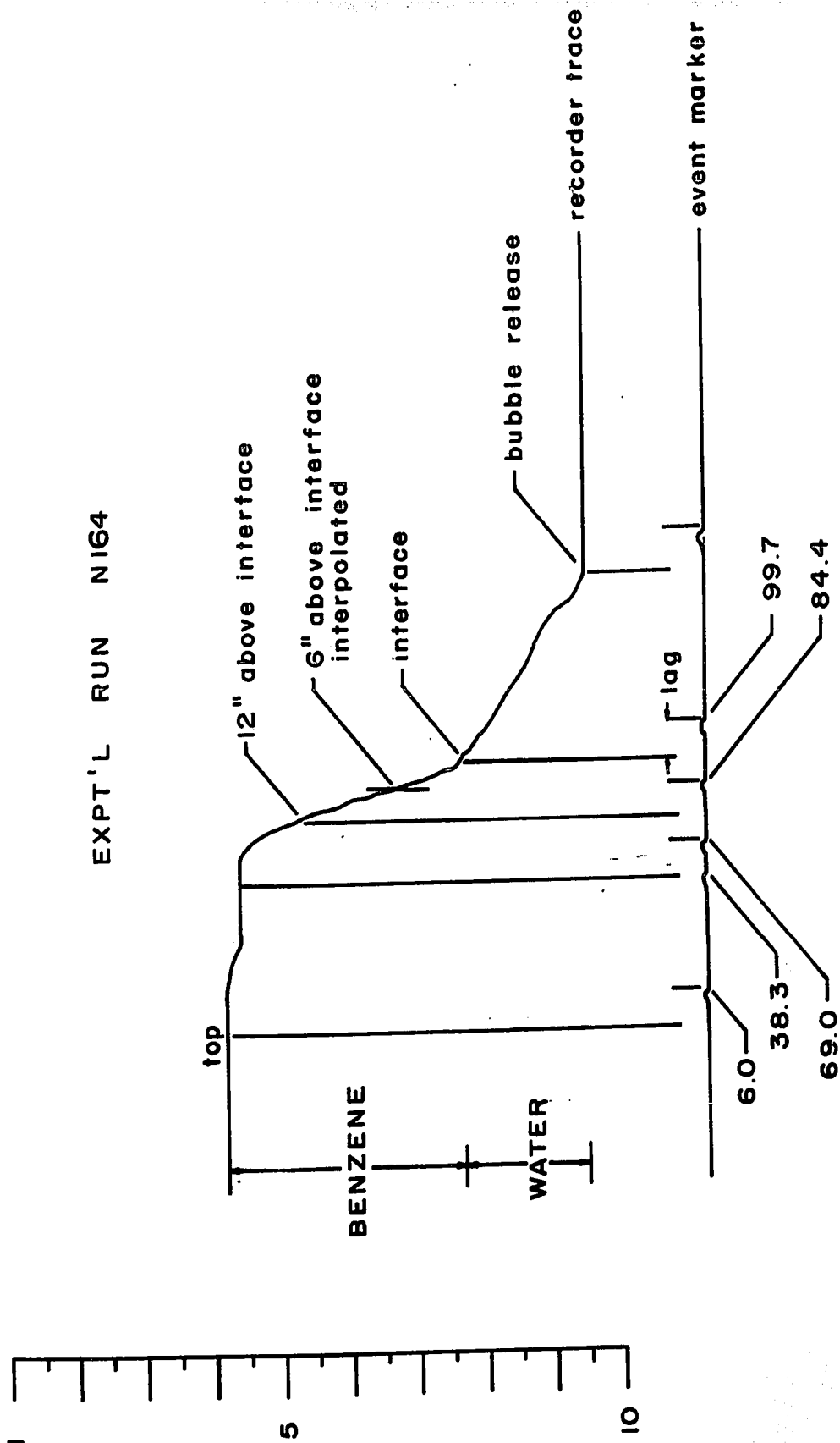


Figure 8

runs when a step change took place near the end of the volume trace as shown in figure 8. This dynamic overshoot of the mercury within the capillary was attributed to high mass-transfer rates when the bubble entered the benzene layer. As a consequence of this dynamic effect, the true volume change was difficult to evaluate for levels greater than 6 inches above the interface.

Nitrogen-benzene, helium-benzene and Freon-14-benzene systems were investigated utilizing water as a forming and calming medium. For the mass-transfer runs, the absolute temperature of the column liquid varied from 294.6 to 298.6 degrees Kelvin. The daily atmospheric pressure varied from 74.5 to 76.5 cm mercury. The experimental data for the mass-transfer runs is tabulated in appendix 1.1.

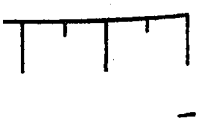
Examination of photographs

Rising velocities of the bubbles were determined by counting the number of dots left by the timing light generator in the margin of the film for a particular length of bubble travel. Bubble travel was measured from the calibrated scale (cm) on the viewing block. The velocity was then determined by;

$$\text{velocity (cm/sec)} = \frac{1000 \times \text{length of bubble travel (cm)}}{\text{number of counted dots (sec)}}$$

Even with the heat absorption shields, enough infra-red radiation struck the column to produce a local temperature rise. This in turn caused the liquid in the column to expand, so that mercury in the precision bore glass capillary began to move. Because of this phenomenon, the existing volume

EXPT. J. T. 1954



measurement apparatus could not be utilized to record bubble volumes. Instead, volumes were calculated from the width and the eccentricity of the spherical cap bubble which had been projected onto a screen. Values of eccentricity were determined simply from the width to height ratio of the bubble. The width of the bubble was found by adjusting the projector-to-screen distance until the centimeter scale on the plexiglass block matched some convenient scale on a metric ruler.

Photographic data for the computation of rise velocities and bubble eccentricities is tabulated in appendix 1.2.

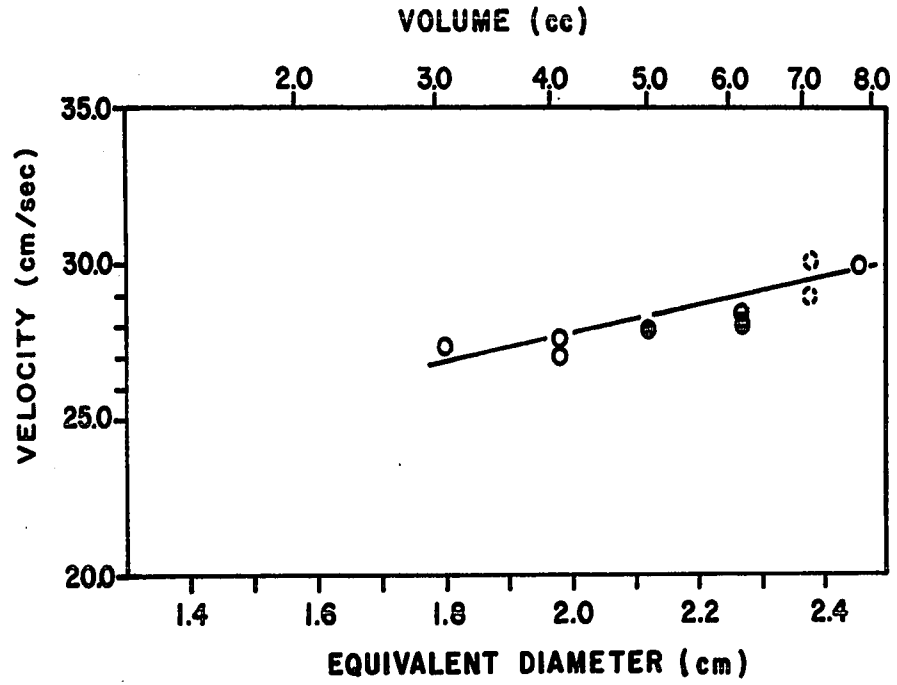
Rise velocity and bubble eccentricity

The rise velocities for nitrogen, helium and freon-14 bubbles are plotted versus the volume of the bubble in figure 9a, over the volume range $1.7 < de < 2.4$. From figure 9a, the rise velocity was determined as a linear function of bubble volume. There was no observed effect of the different carrier gases on the rise velocity. Rise velocities were not determined at the interface due to the presence of a water pressure dome surrounding the bubble as it passed into the benzene layer.

Eccentricities were determined at a point 6 inches above the interface and no effect of the different carrier gases was observed. The eccentricity data for the three systems is plotted in figure 9b versus the volume of the bubble. The eccentricities were taken to be constant over the volume range $1.7 < de < 2.4$.

The rise velocity and eccentricity results are tabulated

FIGURE 9a



- NITROGEN 75 mm lens
- NITROGEN 25 mm lens
- HELIUM 75 mm lens
- FREON - 14 75 mm lens

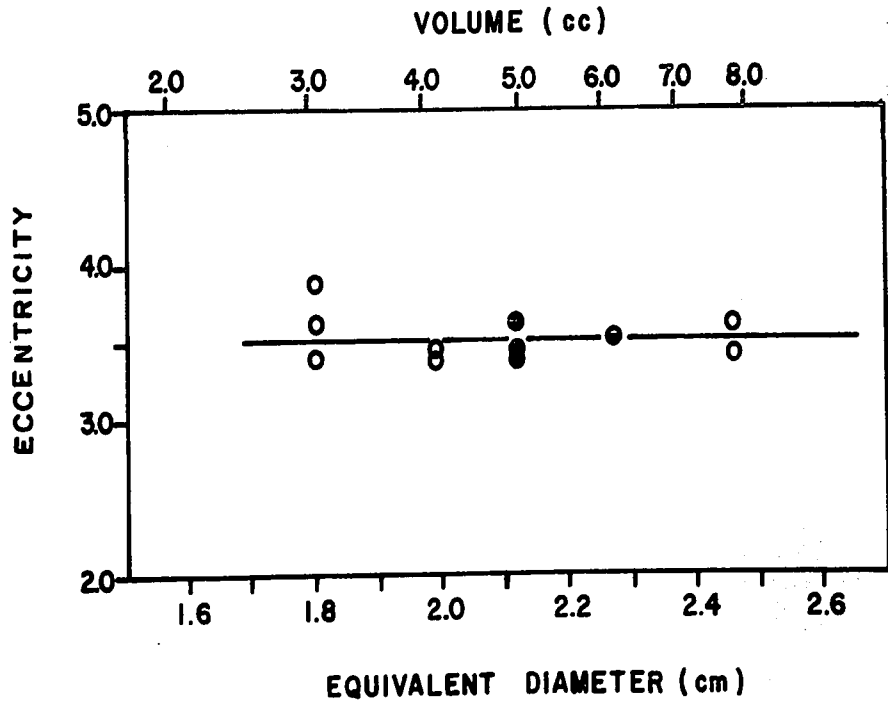


FIGURE 9b

in appendix 2.2.

Mass-transfer area

From photographs of the first 12 inches of the column including the interface, analysis of the bubble wakes showed that entrained water which had been carried through the interface occupied regions at the immediate rear surface of the bubbles as shown in figure 10a and 10b. Consequently, only the frontal surface area of the spherical cap bubble was taken as the mass-transfer area.

Mass-transfer coefficients

Average gas-phase mass-transfer coefficients for the nitrogen-benzene, helium-benzene and Freon-14-benzene systems are plotted versus the average volume of the bubble over the 6 inch mass-transfer interval in figures 11, 12 and 13 respectively, for the volume range $1.7 < d_e < 2.1$. All three plots indicate a slight decrease in the values of K_G with the average volume of the bubble. Through linear curve fits, the average mass-transfer coefficient was obtained as a function of the bubble volume;

Table 1

<u>Carrier gas</u>	<u>Equation for $K_G \times 10^5$</u>
Helium	$K_G = 2.62 - 0.18\bar{V} \pm 0.26$
Nitrogen	$K_G = 2.21 - 0.08\bar{V} \pm 0.42$
Freon-14	$K_G = 1.78 - 0.20\bar{V} \pm 0.13$

VELOCITY (cm/sec)

ECCENTRICITY

PHOTOGRAPH OF BUBBLE FOR
HELIUM-BENZENE SYSTEM

(viewed through perspex block)

75mm Comiscar lens



Figure 10a

PHOTOGRAPH OF BUBBLE FOR
NITROGEN-BENZENE SYSTEM

(25mm Comiscar lens)



(2 pictures per frame)

Figure 10b

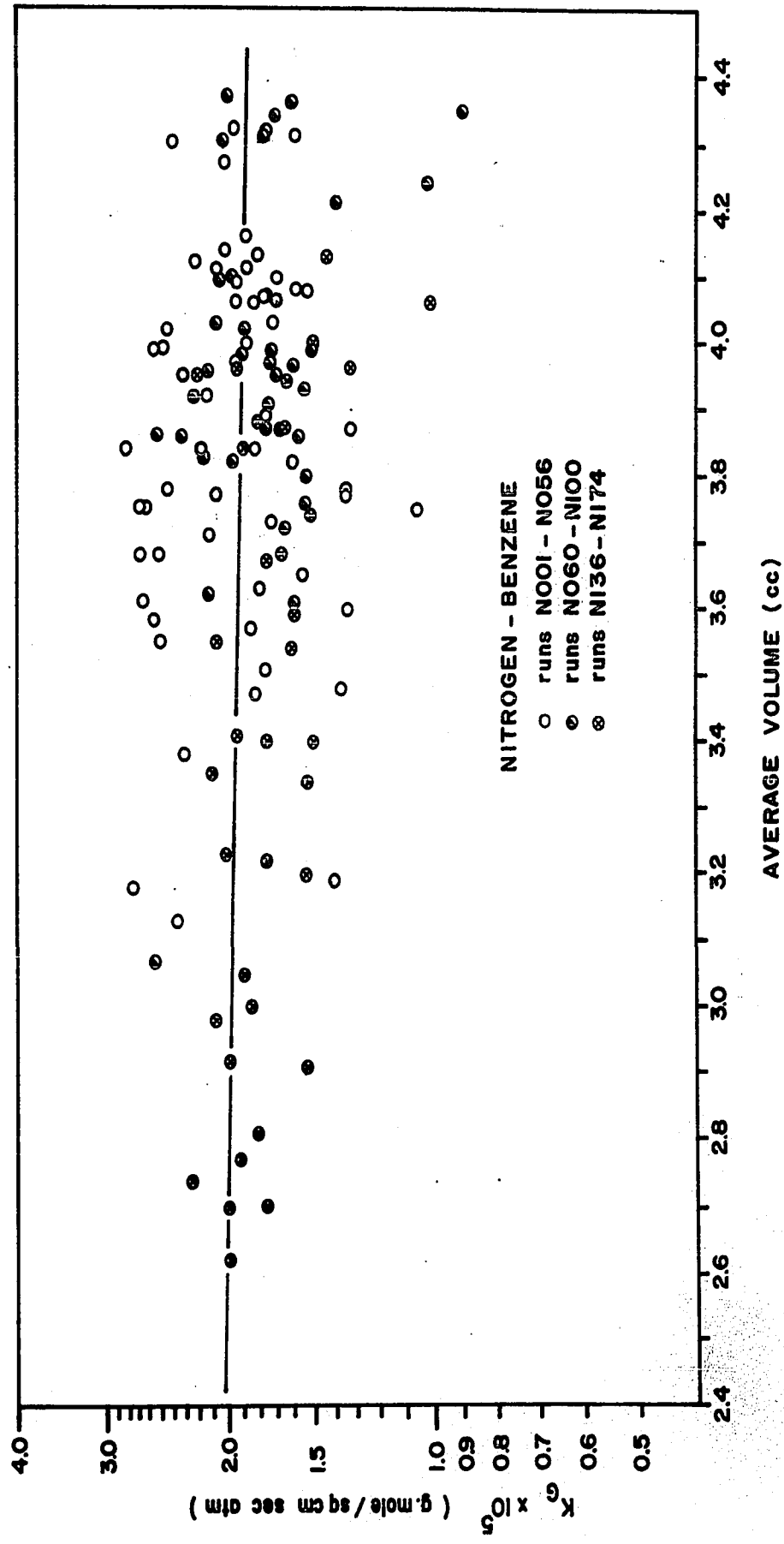


FIGURE 11

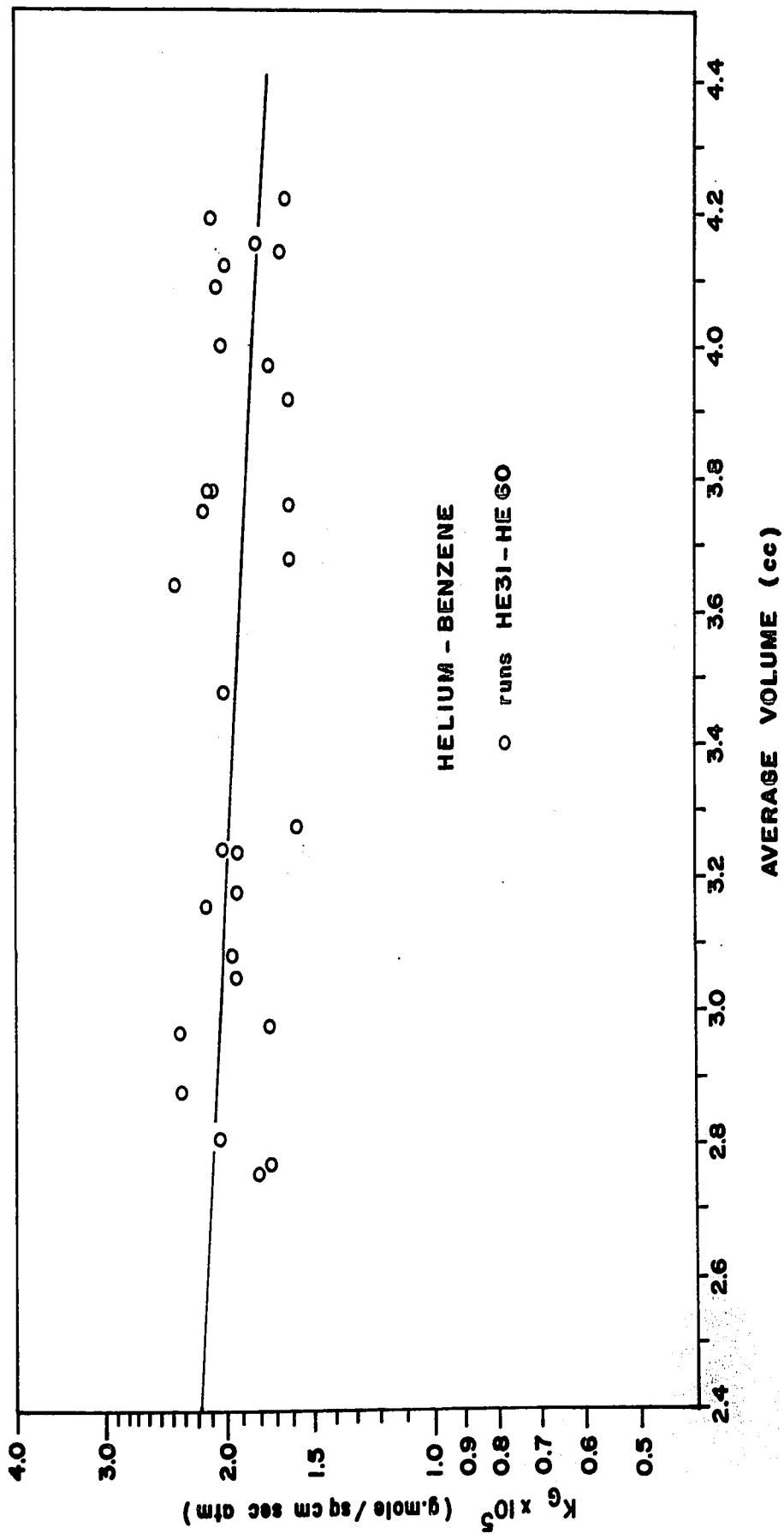


FIGURE 12

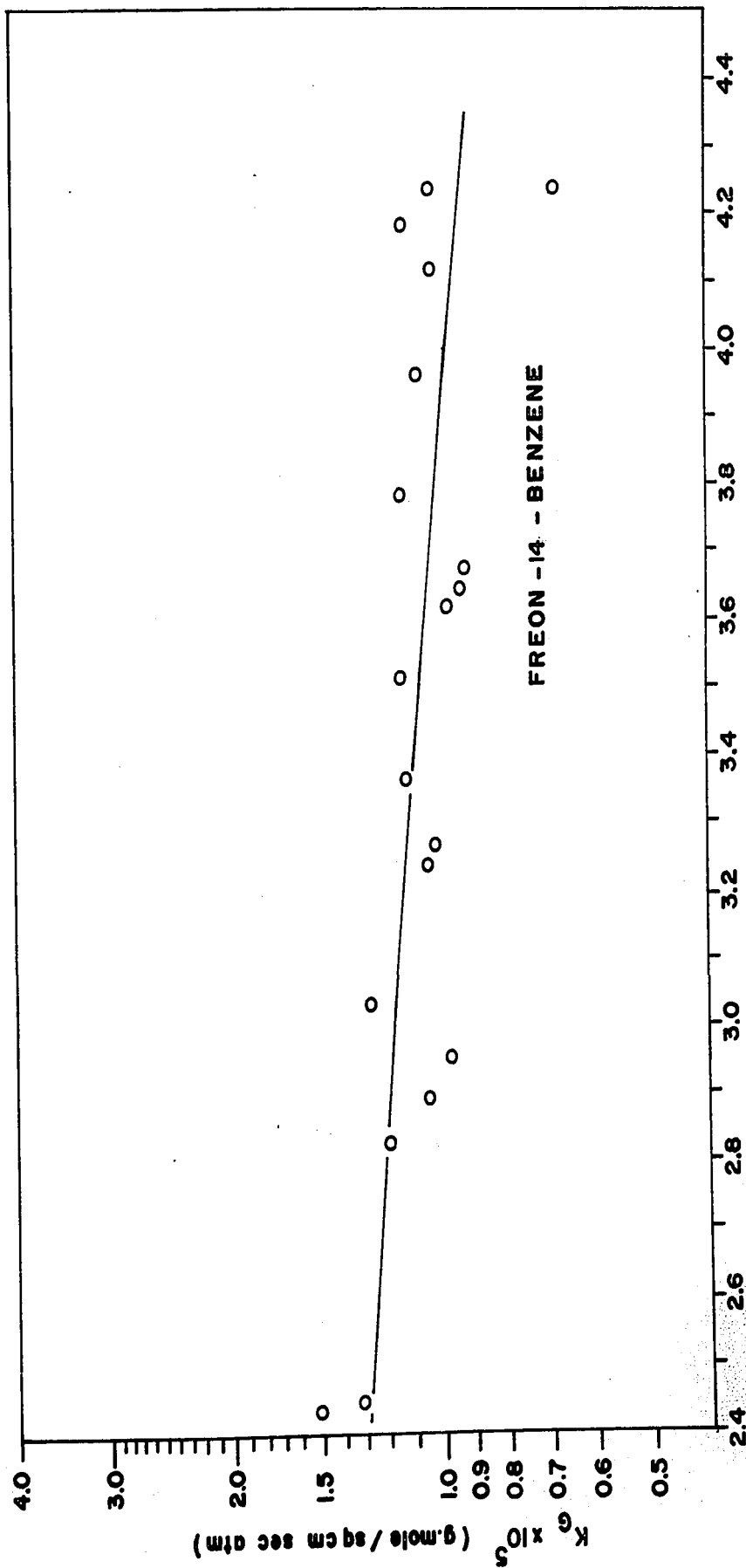
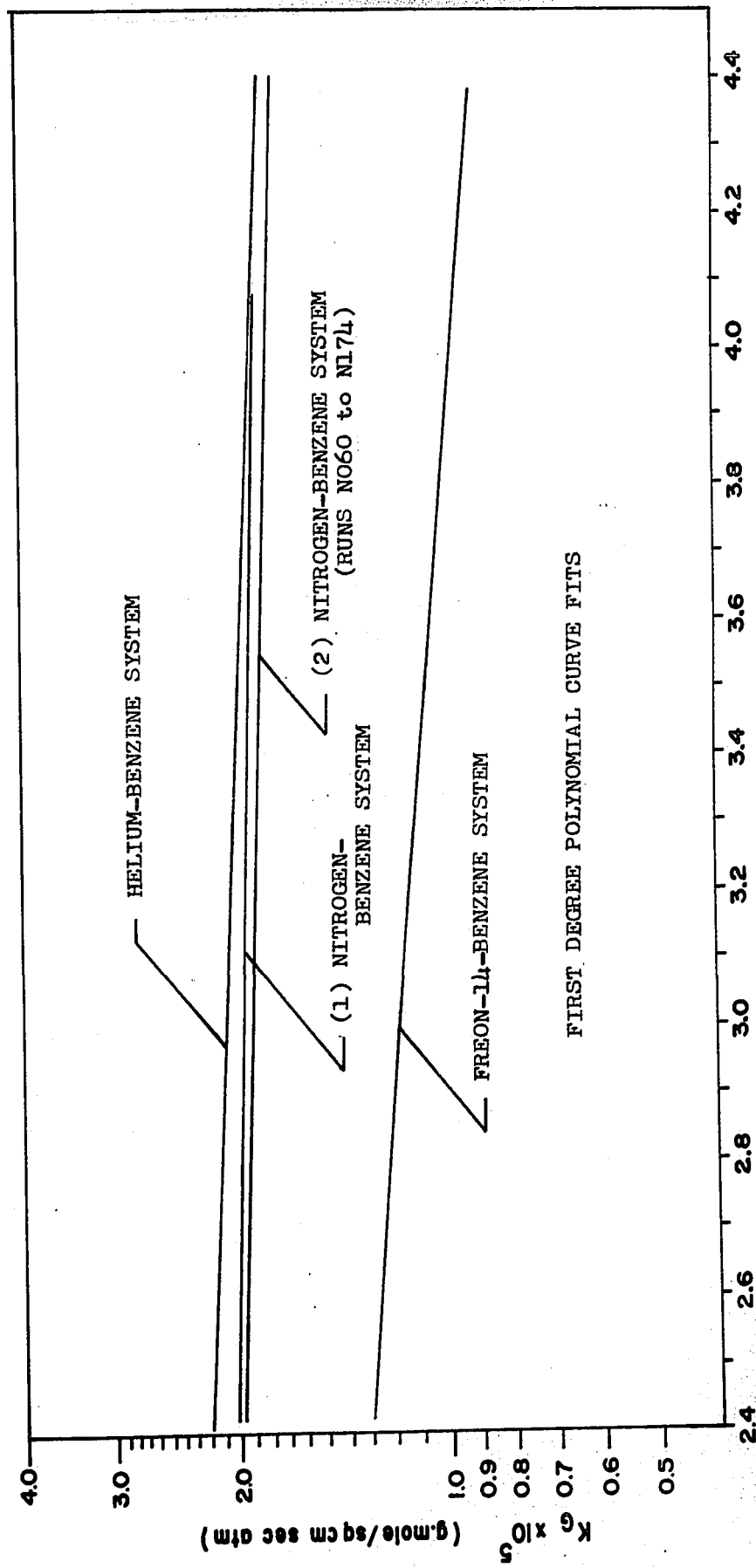


FIGURE 13

Results for the helium-benzene system exhibited the highest K_G values followed by nitrogen and finally by Freon-14, as shown in figure 14. K_G values are tabulated in appendix 2.1 for the three carrier gases. Coefficients for the curve fit K_G data are given in appendix 8. Average K_G values for the volume range $1.7 < d_e < 2.1$ were obtained from a zero-degree polynomial curve fit of the data.

Table 2

<u>Carrier gas</u>	<u>Average $K_G \times 10^5$</u>
Helium	1.99 ± 0.26
Nitrogen	1.90 ± 0.42
Freon-14	1.09 ± 0.13



FIRST DEGREE POLYNOMIAL CURVE FITS

AVERAGE VOLUME (cc)

FIGURE 14

VI. DISCUSSION

Integrated mass-transfer coefficient equation

An integrated form of equation was derived for the evaluation of gas-phase mass-transfer coefficients for the carrier gas-benzene systems employing nitrogen, helium and freon-14. This eliminated the problem of volume-time derivatives, but it was necessary to approximate the integral $\int \frac{dP}{V}$ by the trapezoidal rule. The accuracy of the integrated form of coefficient equation therefore depended on the length of the interval over which it was evaluated. The accuracy of the equation also depended on the evaluation of the system lag and the shape of the recorder trace which was affected by the overshoot of the mercury in the glass capillary for the upper regions of the trace.

Evaluation of bubble volume

The system lag was evaluated by location of the interface position on the recorder trace. It was then possible to assign a bubble volume to a reference level in the column. The effect of the mercury overshoot in the capillary was more difficult to evaluate. The only region of true volume representation was taken to be the first 6 to 8 inches of the benzene layer above the interface. The dashed line in figure 15 shows what is considered to be the true volume change of the bubble in the upper part of the trace. The saturated envelope indicates the bubble's approach to saturation. Mass-transfer coefficients evaluated from volume data at points higher than 6 inches above the interface exhibited a tendency to increase in magnitude for the second 6 inch interval (position 2-3) and become negative for the following 12 inch interval (position 3 to 4).

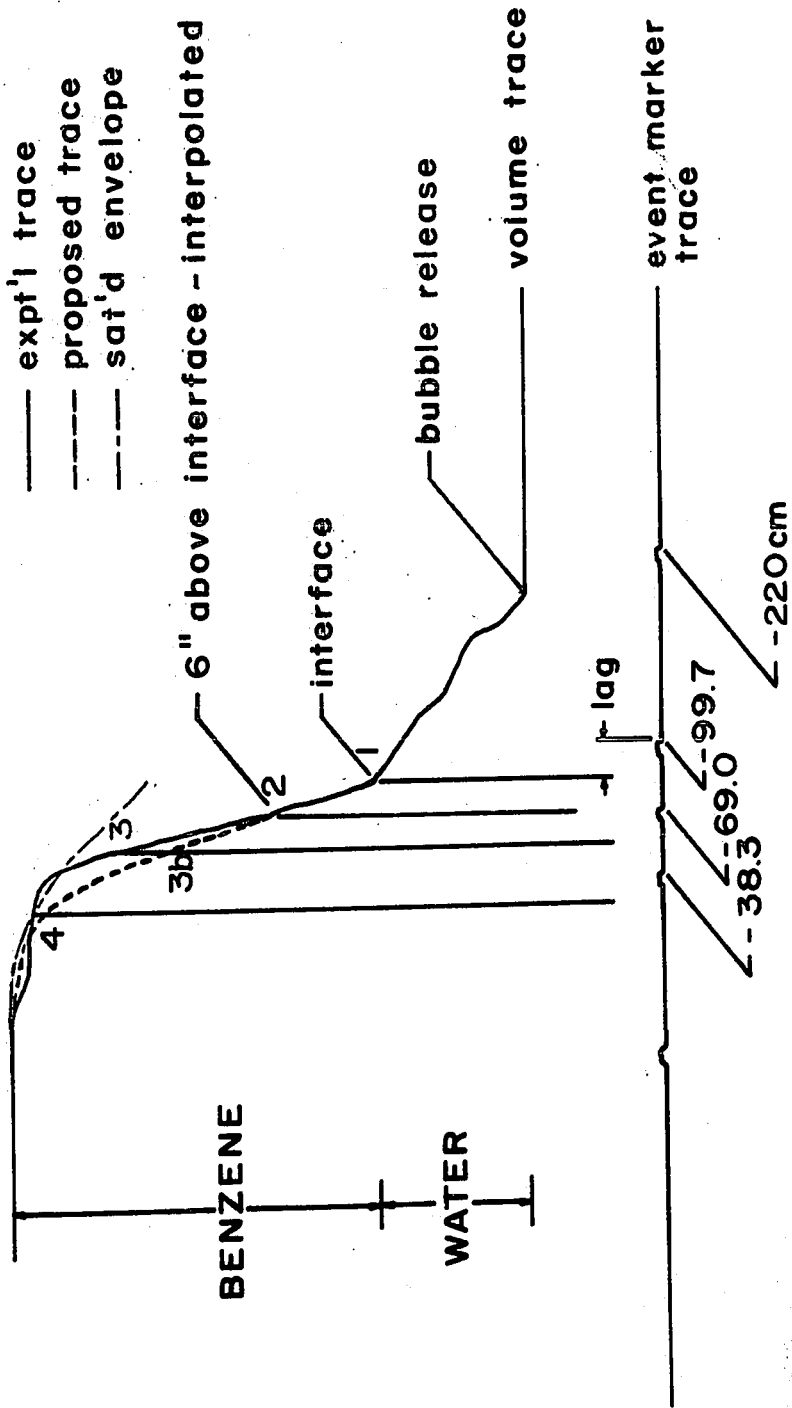


Figure 15

This could be attributed to two effects; a high value of the bubble volume as taken from the recorder trace or precision errors. The first effect would be a result of mercury overshoot as discussed earlier. The second would arise from the precision of the volume measurements when at saturation, PV should be constant. Any small error would yield negative values of K_G on saturation. It should be noted that the dashed line considered to be the true trace, indicated that the bubble does not reach saturation until close to the top of the column and requires confirmation.

Bubble shape

The eccentricity of the spherical cap bubbles over the volume range $1.7 < d_e < 2.4$ remained constant at a value of 3.51. Calderbank (6), for the study of the dissolution of carbon dioxide in water, found that the eccentricity of the spherical cap bubbles were constant for volumes greater than $d_e = 1.5$. The data shows some scatter and this may largely be attributed to the oscillations on the surface of the bubble and deviation from rectilinear motion. In other words, the rear surface of the bubble is not completely circular in cross-section and therefore, major-axis data may vary for the same bubble depending on the direction from which the bubble is viewed. Calderbank reported considerable scatter in his eccentricity data for the volume range $1.4 < d_e < 2.0$. Calderbank's eccentricity data for the volume range $1.8 < d_e < 2.0$ do not vary excessively since the bubbles had attained a fairly stable spherical cap shape. Although some deformation of the bubble surface did occur, it was found that the bubble assumed a stable spherical cap shape in benzene for all three carrier gases over the volume range $1.7 < d_e < 2.4$.

Average mass-transfer coefficients K_G

Plots of K_G values with average bubble volume showed a slight decrease in K_G with bubble volume for all three carrier gases. This could arise from the relative decrease in frontal surface area, sq cm/cubic cm, as the bubble volume was increased. This effect was more pronounced for Freon-14 than for the helium or nitrogen carrier gases. When nitrogen was the carrier gas, the rather small decrease in K_G values could be attributed to the group of data points representing runs N001 to N056. These runs were made at a column temperature approximately five degrees higher than all the other mass-transfer runs. The nitrogen data were curve fitted without runs N001 to N056 and the results are shown below;

Table 3

<u>Nitrogen-Benzene System</u>	<u>Equation for $K_G \times 10^5$</u>
N001-N174	$K_G = 2.21 - 0.08\bar{V} = 0.420$
N060-N174	$K_G = 2.22 - 0.10\bar{V} = 0.404$

Excluding the data for runs N001-N056, the curve fitting programme resulted in a slightly greater dependence on bubble volume.

Initially when comparing the K_G values obtained in this study with the values reported by Golding, Graydon and Johnson (8) who obtained values in the range of $2.8-5.1 \times 10^{-4}$ g.moles/cm² atm sec for bubbles having equivalent diameters of 2.3-2.6 cm when investigating the methanol-water system, the values seemed reasonable. On further examination of the

data, inconsistencies have been found. Firstly, as noted previously, the bubbles were only saturated close to the top of the column. The contact time would have been 3 seconds. If the Vermeulen (16) approximation for diffusion in a sphere is used and the contact time taken for a six inch bubble rise, saturation efficiency values for a 4.19 cc bubble having an equivalent diameter of 2.0 cm would be 93.5%, 64.6% and 51.2% for the helium-benzene, nitrogen-benzene and Freon-14-benzene systems respectively. These values would only be expected to be approximate but do indicate recorded volumes low. A further indication that the data were inconsistent was found by considering the variation of K_G with diffusivity. The diffusivities of benzene vapor in the three carrier gases was calculated using the Wilke-Lee modification of the Hirschfelder-Bird-Spotz equation (9) given in appendix 4. The calculated diffusivities are shown below in Table 4;

Table 4

<u>System</u>	<u>Diffusivity (sq cm/sec)</u>
Helium-benzene	0.373
Nitrogen-benzene	0.097
Freon-14-benzene	0.056

Thus although the variation of the mass-transfer coefficient was in accordance with the direction of change in diffusivity the magnitude of the variation depended on which system was being considered. K_G was roughly proportional to the change in diffusion coefficient when comparing the Freon-14-benzene and nitrogen-benzene systems, but when comparing nitrogen and helium as the carrier gas, there was only a

slight dependence on diffusivity. The photographic studies showed that hydrodynamic conditions were the same for all three systems and would not account for this effect. As a consequence, the accuracy of the volume measurement method must again be questioned and indicated that the dynamic effect might be accompanied by a second lag as the bubble rises through the benzene-water interface. This would result in the volume recorded being low and reduce the magnitude of K_G . It would appear though that the high mass transfer rates preclude the use of the volume measurement method due to the inertia and acceleration effects in the moving mercury column.

VII. CONCLUSIONS

(i) The dynamic effect caused by inertia and acceleration of the mercury in the volume measurement apparatus limited the scope of this work.

(ii) Consideration of the calculated mass transfer coefficient values indicated that although the direction of the variation of K_G is in accordance with the variation of the diffusivity of benzene in the carrier gases the K_G values must be considered low. This is particularly true for helium carrier gas.

(iii) Bubbles were in the volume range corresponding to 1.7 to 2.1, and assumed a spherical cap shape. The eccentricity remained constant at 3.5 for all three carrier gases and bubble oscillations were small.

(iv) Bubble velocities were in agreement with values reported in the literature.

VIII. RECOMMENDATIONS

Due to the dynamic effect in the volume measurement apparatus, this method requires re-evaluation. Volumes must be recorded instantaneously for the calculation of instantaneous mass-transfer coefficients. Bubble volumes may be measured indirectly by recording pressure changes within the column of liquid with sensitive pressure measurement devices such as a micromanometer. As an alternative to the volume measurement method used in this work, the pressure measurement method of Calderbank and Lochiel (6) could be used although the temperature history of the dead air space might have to be taken into account as pointed out by Baird (7). Some consideration could be given to the more recent method developed by Calderbank, Johnson and Loudon (10).

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APPENDICES

APPENDIX 1.

EXPERIMENTAL DATA

1. Recorder trace data: The data given on each page are for a specific atmospheric pressure and column temperature. Points at which data were taken from the chart recorder trace are indicated by distances below the datum line at the top of the column.
2. Bubble velocity and Eccentricity data
3. Density of benzene
4. Solubility of helium, nitrogen and Freon-14 in benzene
5. Vapor pressure of benzene

1. Recorder
2. Bottle
3. Density
4. Solvent
5. Ascorbic

TABLE AI-1

EXPERIMENTAL DATA

CARRIER GAS: NITROGEN		MEDIUM: BENZENE	
ATMOSPHERIC PRESSURE: 76.0 CM HG			
COLUMN TEMPERATURE: 298.6 DEG K			
INITIAL VDL	RECORDER READING AT INDICATED LEVEL IN COLUMN		
RUN NO.	CM HG TRAVEL	INITIAL	
N001	50.25	1.0000	1.0 CM
N002	50.25	0.9850	16.5 CM
N003	51.40	0.9500	52.5 CM
		0.8600	0.4550
		0.8500	0.3700
		0.9200	0.4375
			0.4750
			0.3675
			0.4150

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: NITROGEN

ATMOSPHERIC PRESSURE: 75.7 CM HG

COLUMN TEMPERATURE: 296.9 DEG K

RUN NO.	CM HG TRAVEL	INITIAL	95.4 CM	69.0 CM	52.5 CM	16.5 CM	1.0 CM
N010	50.65	0.9825	0.8650	0.7000	0.4925	0.4500	0.4075
N011	44.35	0.9725	0.8950	0.7125	0.5475	0.5400	0.4925
N012	50.10	0.9875	0.8725	0.6900	0.5050	0.4425	0.4200
N013	53.15	0.9975	0.8750	0.6700	0.5050	0.4625	0.4150
N014	52.70	0.9775	0.8125	0.6300	0.4450	0.3975	0.3850
N015	53.50	0.9850	0.8850	0.7000	0.4950	0.4300	0.3800
N016	51.25	0.9950	0.8900	0.7000	0.5250	0.4875	0.4250



EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: NITROGEN

ATMOSPHERIC PRESSURE: 75.9 CM HG

COLUMN TEMPERATURE: 298.3 DEG K

RECORDER READING AT INDICATED LEVEL IN COLUMN

1.0 CM

16.5 CM

52.5 CM

69.0 CM

85.4 CM

INITIAL

CM HG TRAVEL

RUN NO.

RUN NO.	INITIAL	85.4 CM	69.0 CM	52.5 CM	16.5 CM	1.0 CM
N018	0.9775	0.8750	0.7200	0.5475	0.5150	0.4575
N019	0.9750	0.8575	0.7000	0.5300	0.5000	0.4400
N020	0.9600	0.8125	0.6700	0.5150	0.4700	0.4100
N021	0.9700	0.8325	0.6800	0.4875	0.4600	0.4300
N022	0.9650	0.8275	0.6800	0.5250	0.4900	0.4500
N023	0.9675	0.8675	0.6820	0.5575	0.5275	0.4950
N024	0.9850	0.8100	0.7080	0.5200	0.5000	0.4600
N025	0.9650	0.8700	0.7000	0.5600	0.5375	0.4650
N026	0.9850	0.8275	0.6800	0.4750	0.4350	0.3720
N027	0.9725	0.8325	0.6800	0.5075	0.4850	0.4100
N028	0.9850	0.8525	0.6600	0.4775	0.4450	0.4100
N029	0.9850	0.8525	0.6600	0.5075	0.4750	0.4350
N030	0.9850	0.8525	0.6600	0.4850	0.4450	0.4100
N031	0.9700	0.8525	0.6600	0.4850	0.4450	0.4100
N032	0.9820	0.8525	0.6600	0.4850	0.4450	0.4100
N033	0.9850	0.8525	0.6600	0.4850	0.4450	0.4100
N034	0.9750	0.8525	0.6600	0.4850	0.4450	0.4100
N035	0.9750	0.8525	0.6600	0.4850	0.4450	0.4100
N036	0.9800	0.8525	0.6600	0.4850	0.4450	0.4100
N037	0.9800	0.8525	0.6600	0.4850	0.4450	0.4100

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: NITROGEN

ATMOSPHERIC PRESSURE: 76.2 CM HG

COLUMN TEMPERATURE: 295.8 DEG K

RUN NO.	CM HG TRAVEL	INITIAL	85.4 CM	69.0 CM	52.5 CM	16.5 CM	1.0 CM
N038	48.25	0.9700	0.8775	0.7250	0.5425	0.5000	0.4600
N039	45.55	0.9550	0.8500	0.7175	0.5375	0.4850	0.4500
N040	47.15	0.9675	0.9125	0.7500	0.5725	0.5350	0.5050
N041	47.10	0.9725	0.8600	0.7350	0.5625	0.5100	0.4650
N042	45.60	0.9800	0.8950	0.7500	0.5975	0.5775	0.5200
N043	47.20	0.9625	0.8525	0.7050	0.5525	0.5200	0.4675
N044	45.20	0.9550	0.9125	0.7400	0.6000	0.5800	0.5200
N045	47.40	0.9950	0.9125	0.7500	0.5875	0.5650	0.5000
N046	46.25	0.9750	0.8300	0.7225	0.5600	0.5175	0.4550

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: NITROGEN

76.2 CM HG

ATMOSPHERIC PRESSURE:

298.7 DEG K

COLUMN TEMPERATURE:

RECORDER READING AT INDICATED LEVEL IN COLUMN

1.0 CM

16.5 CM

52.5 CM

69.0 CM

85.4 CM

INITIAL
CM HG TRAVEL

RUN NO.	INITIAL CM HG TRAVEL	85.4 CM	69.0 CM	52.5 CM	16.5 CM	1.0 CM
NO47	48.75	0.8950	0.7450	0.5625	0.5075	0.4325
NO48	50.85	0.9125	0.7400	0.5550	0.4600	0.4050
NO49	50.45	0.8400	0.6900	0.5160	0.3920	0.3250
NO50	50.95	0.8550	0.6700	0.4950	0.4250	0.3500
NO51	50.75	0.8525	0.7000	0.5175	0.4150	0.3450
NO52	51.20	0.8750	0.6900	0.5100	0.4400	0.3700
NO53	51.65	0.9100	0.7400	0.5000	0.4475	0.3675
NO54	51.40	0.8850	0.7150	0.5200	0.4275	0.3475
NO55	50.35	0.8225	0.7200	0.5200	0.4700	0.4025

EXPERIMENTAL DATA

CARRIER GAS: NITROGEN MEDIUM: BENZENE

ATMOSPHERIC PRESSURE: 75.5 CM HG

COLUMN TEMPERATURE: 295.3 DEG K

INITIAL VOL	RECORDER READING AT INDICATED LEVEL IN COLUMN
49.95	0.7325
52.25	0.7425
51.40	0.7525

CM HG TRAVEL	INITIAL	99.7 CM	84.4 CM	69.0 CM	38.3 CM	19.0 CM
NC60	0.9775	0.6050	0.4000	0.3275	0.2250	0.3250
NC61	0.9700	0.6000	0.3850	0.2200	0.2200	0.2200
NC62	0.9850	0.6025	0.3800	0.2250	0.2250	0.2250

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: NITROGEN

ATMOSPHERIC PRESSURE: 75.6 CM HG

COLUMN TEMPERATURE: 295.3 DEG K

RUN NO.	INITIAL VOL		RECORDER READING AT INDICATED LEVEL IN COLUMN					
	CM	HG TRAVEL	INITIAL	99.7 CM	84.4 CM	69.0 CM	38.3 CM	19.0 CM
NO63	51.40		0.9800	0.7600	0.5975	0.4900	0.3100	0.3050
NO64	55.55		0.9675	0.7300	0.5800	0.3700	0.2300	0.2275
NO65	47.60		0.9800	0.7750	0.6425	0.4500	0.3275	0.3275
NO67	47.95		0.9775	0.7675	0.6100	0.4125	0.3025	0.2800
NO68	48.40		0.9750	0.7525	0.6300	0.4350	0.3150	0.2925
NO69	43.20		0.9675	0.7850	0.6375	0.4700	0.3950	0.3725

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: NITROGEN

76.0 CM HG

ATMOSPHERIC PRESSURE:

295.3 DEG K

COLUMN TEMPERATURE:

RECORDER READING AT INDICATED LEVEL IN COLUMN

19.0 CM

38.3 CM

69.0 CM

84.4 CM

99.7 CM

INITIAL

INITIAL VOL

CM HG TRAVEL

RUN NO.	INITIAL VOL	CM HG TRAVEL	INITIAL	99.7 CM	84.4 CM	69.0 CM	38.3 CM	19.0 CM
N070	51.70		0.9800	0.7800	0.6750	0.4625	0.3350	0.3200
N071	47.60		1.0000	0.7800	0.6525	0.4600	0.3350	0.3300
N072	48.90		0.9775	0.7575	0.6000	0.3850	0.2925	0.2900
N073	50.40		0.9725	0.7200	0.5700	0.3550	0.2925	0.2900
N074	47.45		0.9850	0.7450	0.6050	0.4325	0.3375	0.3250
N075	46.05		0.9875	0.7725	0.6200	0.4375	0.3275	0.3250
N076	48.00		0.9875	0.7625	0.6200	0.4225	0.3175	0.3150
N077	47.40		0.9600	0.7500	0.6025	0.4200	0.3200	0.3150
N078	46.80		0.9800	0.7200	0.5725	0.3600	0.2700	0.2700

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: NITROGEN

ATMOSPHERIC PRESSURE: 76.5 CM HG

COLUMN TEMPERATURE: 295.3 DEG K

RUN NO.	INITIAL VOL CM HG TRAVEL	INITIAL	99.7 CM	84.4 CM	69.0 CM	38.3 CM	19.0 CM
N079	53.80	0.99275	0.8125	0.7125	0.5150	0.3625	0.3575
N080	47.45	0.9725	0.7500	0.6050	0.3800	0.2650	0.2425
N081	47.10	0.9600	0.7775	0.6425	0.4675	0.3575	0.3050
N082	45.80	0.9550	0.7325	0.5950	0.4200	0.3175	0.3050
N083	35.25	0.9750	0.7675	0.6275	0.4500	0.3550	0.3375
N084	44.30	0.9700	0.7700	0.6350	0.4650	0.3625	0.3550
N085	44.80	0.9725	0.7625	0.6325	0.4650	0.3625	0.3625
N086	43.85	0.9725	0.7900	0.6600	0.5000	0.4050	0.3825
N087	43.05	0.9900	0.7925	0.6800	0.4850	0.3575	0.3300
N088							

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: NITROGEN

ATMOSPHERIC PRESSURE: 76.1 CM HG

COLUMN TEMPERATURE: 295.3 DEG K

RUN NO.	INITIAL VOL CM HG TRAVEL	INITIAL	99.7 CM	84.4 CM	69.0 CM	38.3 CM	19.0 CM
N089	50.65	0.9800	0.6875	0.5250	0.4000	0.3300	0.3150
N090	47.10	0.9600	0.7250	0.5750	0.4125	0.3125	0.2950
N091	46.95	0.9525	0.7400	0.5850	0.4400	0.3600	0.3500
N092	44.50	0.9725	0.7575	0.6350	0.4450	0.3625	0.3405
N093	45.75	0.9950	0.7875	0.6250	0.4400	0.3650	0.3320
N094	45.05	0.9850	0.7500	0.5900	0.4275	0.3450	0.3300
N095	46.40	0.9850	0.7575	0.6300	0.4700	0.3625	0.3450
N096	46.75	0.9800	0.7575	0.6300	0.4300	0.3575	0.3350
N097	46.05	0.9700	0.7800	0.6100	0.4300	0.3575	0.3350
N098	45.55	0.9525	0.7225	0.5850	0.4400	0.3600	0.3350
N100	45.55	0.9800	0.7800	0.6350	0.4500	0.3800	0.3500

RECORDER READING AT INDICATED LEVEL IN COLUMN

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: NITROGEN

ATMOSPHERIC PRESSURE: 75.5 CM HG

COLUMN TEMPERATURE: 294.6 DEG K

RUN NO.	INITIAL VOL CM HG TRAVEL	INITIAL	99.7 CM	84.4 CM	69.0 CM	38.3 CM	6.0 CM
1136	46.95	0.955	0.782	0.500	0.400	0.300	0.200
1137	47.00	0.980	0.690	0.630	0.465	0.350	0.250
1138	47.90	0.980	0.765	0.630	0.470	0.350	0.250
1141	45.65	0.970	0.775	0.630	0.480	0.350	0.250
1142	47.15	0.980	0.765	0.645	0.490	0.350	0.250
1143	47.40	0.982	0.780	0.650	0.500	0.350	0.250
1144	46.70	0.985	0.762	0.645	0.500	0.350	0.250
1145	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1146	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1147	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1148	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1149	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1150	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1151	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1152	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1153	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1154	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1155	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1156	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1157	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1158	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1159	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1160	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1161	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1162	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1163	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1164	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1165	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1166	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1167	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1168	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1169	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1170	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1171	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1172	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1173	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1174	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1175	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1176	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1177	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1178	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1179	47.65	0.985	0.762	0.645	0.500	0.350	0.250
1180	47.65	0.985	0.762	0.645	0.500	0.350	0.250

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: HELIUM

ATMOSPHERIC PRESSURE: 73.0 CM HG

COLUMN TEMPERATURE: 294.6 DEG K

RUN NO.	CM HG TRAVEL	INITIAL	99.7 CM	84.4 CM	69.0 CM	38.3 CM	6.0 CM
HE31	49.85	0.9700	0.7500	0.5850	0.3950	0.2125	0.1350
HE32	45.50	0.9700	0.7950	0.6275	0.4200	0.2350	0.1350
HE33	49.50	0.9800	0.7700	0.5900	0.4000	0.2275	0.1275
HE34	47.95	0.9675	0.7200	0.5600	0.3875	0.2250	0.1200
HE35	44.50	0.9425	0.7250	0.5700	0.3875	0.2250	0.1200
HE36	44.45	0.9725	0.7700	0.6150	0.4400	0.2315	0.1250
HE37	41.75	0.9525	0.7850	0.6450	0.4750	0.2380	0.1300
HE38	42.60	0.9350	0.7350	0.5750	0.4025	0.2300	0.1250
HE39	47.40	0.9350	0.7200	0.5675	0.4150	0.2300	0.1250
HE40	38.15	0.9375	0.7650	0.6300	0.4950	0.2850	0.1850
HE41	35.65	0.9800	0.7925	0.6600	0.5100	0.3000	0.2000
HE42	32.60	0.9875	0.7825	0.6600	0.5275	0.3150	0.2150
HE43	32.70	0.9800	0.8000	0.6950	0.5380	0.3475	0.2350
HE44		0.9500	0.8000	0.6950	0.5380	0.3475	0.2350
HE45							

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: HELIUM

74.2 CM HG

ATMOSPHERIC PRESSURE:

294.6 DEG K

COLUMN TEMPERATURE:

RECORDER READING AT INDICATED LEVEL IN COLUMN

RUN NO.	INITIAL VOL CM HG TRAVEL	INITIAL	99.7 CM	84.4 CM	69.0 CM	38.3 CM	6.0 CM
HE46	48.90	0.9425	0.7200	0.5650	0.3750	0.2500	0.1250
HE47	50.15	0.9700	0.7550	0.6150	0.4150	0.2350	0.1150
HE48	47.55	0.9950	0.7775	0.6350	0.4525	0.2900	0.1375
HE49	49.75	0.9750	0.7725	0.6450	0.4100	0.2300	0.1100
HE50	43.60	0.9875	0.8125	0.7100	0.5900	0.4100	0.2300
HE51	39.10	0.9800	0.8000	0.7000	0.5450	0.4100	0.2300
HE52	36.50	0.9825	0.8500	0.7300	0.6200	0.4500	0.2300
HE53	35.30	0.9675	0.8000	0.6900	0.5500	0.4100	0.2300
HE54	33.75	0.9775	0.8200	0.6400	0.4950	0.3200	0.1500
HE55	43.45	0.9700	0.7650	0.6400	0.4950	0.3200	0.1500
HE56	38.60	0.9600	0.7900	0.6650	0.5125	0.4100	0.2300
HE57	34.60	0.9675	0.7875	0.6550	0.5225	0.4100	0.2300

EXPERIMENTAL DATA

MEDIUM: BENZENE

CARRIER GAS: FREON

ATMOSPHERIC PRESSURE: 74.5 CM HG

COLUMN TEMPERATURE: 294.6 DEG K

RUN NO.	INITIAL VOL CM HG TRAVEL	INITIAL	99.7 CM	84.4 CM	69.0 CM	38.3 CM	6.0 CM
FR01	50.05	0.9555	0.7250	0.6150	0.4725	0.3105	0.2200
FR02	50.80	0.9625	0.7350	0.6225	0.4600	0.3000	0.2250
FR03	49.15	0.9600	0.7250	0.6225	0.4700	0.3000	0.2250
FR04	44.15	0.9825	0.7825	0.6800	0.5500	0.4100	0.3000
FR05	43.15	0.9800	0.7700	0.6800	0.5500	0.4100	0.3000
FR06	41.90	0.9800	0.7825	0.6800	0.5625	0.4175	0.3000
FR07	38.30	0.9600	0.7825	0.6950	0.5700	0.4450	0.3000
FR08	34.05	0.9750	0.8250	0.7400	0.6300	0.5025	0.3000
FR09	29.40	0.9750	0.8575	0.7775	0.6700	0.5025	0.3000
FR10	28.65	0.9875	0.8450	0.7575	0.6575	0.6050	0.3000

EXPERIMENTAL DATA

CARRIER GAS: FFEON	MEDIUM: BENZENE
ATMOSPHERIC PRESSURE: 75.6 CM HG	
COLUMN TEMPERATURE: 294.1 DEG K	
INITIAL VOL	RECORDER READING AT INDICATED LEVEL IN COLUMN
RUN NO. CM HG TRAVEL INITIAL	99.7 CM 84.4 CM 69.0 CM 38.3 CM 6.0 CM
FRI 1 39.35	0.8200 0.7375 0.6150 0.5100 0.5000
FRI 2 35.80	0.8275 0.7375 0.6400 0.5425 0.5375
FRI 3 36.75	0.8200 0.7425 0.6400 0.5425 0.5350
FRI 4 37.25	0.7300 0.6300 0.5000 0.3350 0.3200
FRI 5 50.55	0.7300 0.6500 0.4900 0.3150 0.3000
FRI 6 43.55	0.7650 0.6750 0.5250 0.4025 0.3950
FRI 7 43.20	0.7800 0.6900 0.5450 0.3975 0.3950
FRI 8 40.05	
FRI 9	

2. Velocity and Eccentricity data

Table A1-2

<u>Photographic run number</u>	<u>Carrier gas</u>	<u>Bubble width (cm)</u>	<u>Bubble height (cm)</u>	<u>Bubble travel (cm)</u>	<u>No. of dots counted in film margin</u>
4	nitrogen	3.30	0.95	3.0	109
		3.20	0.95		
		3.20	0.95		
5	nitrogen	4.00	1.10	3.0	100
		3.95	1.15		
		3.95	1.15		
8	nitrogen	3.10	0.80	4.0	146
		2.90	0.80		
		2.90	0.85		
9	Freon-14	3.45	1.00	2.0	72
		3.40	1.00		
		3.45	0.95		
10	helium	3.70	1.05	3.0	108
		3.70	1.05	2.0	71

data taken from photographs with 75 mm Comiscar lens

3. Density of benzene

Table A1-3

<u>Temperature (°c)</u>	<u>Density (g./ml)</u> ⁽¹¹⁾
20.0	0.8790
25.0	0.8737
30.0	0.8685
40.0	0.8577

4. Solubility data

Table A1-4

<u>Carrier gas</u>	<u>Temperature (°c)</u>	<u>Mole fraction x10⁴</u>
nitrogen (12)	20.0	4.210
	40.0	4.810
helium (13)	25.0	0.786
Freon-14 (14)	5.80	5.410

5. Vapor pressure of benzene

Table A1-5

<u>Vapor pressure</u> ⁽¹⁵⁾ <u>(mm Hg)</u>	<u>Temperature</u> <u>(°c)</u>
60.0	15.4
100.0	26.1

APPENDIX 2.

EXPERIMENTAL RESULTS AND CALCULATIONS

1. Gas-phase mass-transfer coefficients K_G
2. Velocity and Eccentricity results
3. Evaluation of K_G , variables involved, sample calculation

TABLE A2-1
EXPERIMENTAL RESULTS

RUN NO.	KG COEFFICIENT (ATM SEC SQCM)	AVERAGE VOLUME (CC)	EQUIVALENT DIAMETER (CM)	FRONTAL AREA (SQCM)	VELOCITY (CM/SEC)	MOLES TRANSFERRED (G. MOLES)	ECCENTRICITY
N001	0.1540E-04	4.078	1.982	10.68	28.26	0.9580E-05	3.51
N002	0.1934E-04	4.091	1.984	10.70	28.26	0.1143E-04	3.51
N003	0.2438E-04	4.018	1.972	10.57	28.23	0.1335E-04	3.51
N004	0.1598E-04	4.084	1.983	10.69	28.26	0.9171E-05	3.51
N005	0.1965E-04	3.975	1.965	10.50	28.21	0.1053E-04	3.51
N006	0.2555E-04	3.989	1.988	10.52	28.21	0.1275E-04	3.51
N007	0.2094E-04	4.141	1.992	10.79	28.29	0.1137E-04	3.51
N008	0.2800E-04	3.842	1.943	10.26	28.15	0.1321E-04	3.51
N009	0.1577E-04	4.307	2.019	11.08	28.36	0.9415E-05	3.51
N010	0.1793E-04	4.074	1.982	10.67	28.25	0.9958E-05	3.51
N011	0.2575E-04	3.558	1.894	9.75	28.02	0.1174E-04	3.51
N012	0.1840E-04	4.069	1.981	10.65	28.25	0.1015E-04	3.51
N013	0.2086E-04	4.118	1.989	10.75	28.27	0.1124E-04	3.51
N014	0.2396E-04	4.301	2.018	11.07	28.36	0.1281E-04	3.51
N015	0.1966E-04	4.321	2.021	11.10	28.37	0.1112E-04	3.51
N016	0.2039E-04	4.271	2.013	11.01	28.34	0.1133E-04	3.51
N017	0.2230E-04	4.118	1.989	10.75	28.27	0.1179E-04	3.51
N018	0.1774E-04	3.513	1.886	9.67	28.00	0.9519E-05	3.51
N019	0.1845E-04	3.474	1.879	9.60	27.98	0.9726E-05	3.51
N020	0.1343E-04	3.600	1.902	9.83	28.04	0.7797E-05	3.51
N021	0.1874E-04	3.575	1.897	9.73	28.03	0.1004E-04	3.51
N022	0.1358E-04	3.481	1.880	9.61	27.98	0.7865E-05	3.51
N023	0.2769E-04	3.179	1.824	9.05	27.95	0.1212E-04	3.51
N024	0.1831E-04	4.006	1.970	10.55	28.22	0.1091E-04	3.51
N025	0.2326E-04	3.378	1.822	9.42	27.94	0.1127E-04	3.51
N026	0.1414E-04	3.190	1.826	9.07	27.95	0.7473E-05	3.51
N027	0.2385E-04	3.134	1.816	8.98	27.93	0.1085E-04	3.51
N028	0.1610E-04	3.815	1.939	10.22	28.14	0.9868E-05	3.51
N029	0.1735E-04	3.729	1.924	10.06	28.10	0.1029E-04	3.51

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RUN NO.	EXPERIMENTAL RESULTS							ECCENTRICITY
	KG COEFFICIENT (G.MOLE) ----- (ATM SEC SQCM)	AVERAGE VOLUME (CC)	EQUIVALENT DIAMETER (CM)	FRONTAL AREA (SQCM)	VELOCITY (CM/SEC)	MOLES TRANSFERRED (G.MOLES)		
N030	0.2650E-04	3.615	1.904	9.86	28.04	0.1368E-04	3.51	
N031	0.2181E-04	3.841	1.943	10.26	28.15	0.1244E-04	3.51	
N032	0.2683E-04	3.697	1.918	10.00	28.08	0.1401E-04	3.51	
N033	0.2130E-04	3.915	1.956	10.39	28.18	0.1240E-04	3.51	
N034	0.2547E-04	3.681	1.916	9.98	28.07	0.1346E-04	3.51	
N035	0.2461E-04	3.782	1.933	10.16	28.12	0.1340E-04	3.51	
N036	0.2589E-04	3.752	1.928	10.10	28.11	0.1416E-04	3.51	
N037	0.1559E-04	3.787	1.934	10.17	28.12	0.8589E-05	3.51	
N038	0.1858E-04	3.844	1.943	10.27	28.15	0.9257E-05	3.51	
N039	0.1558E-04	3.649	1.910	9.92	28.06	0.7865E-05	3.51	
N040	0.2139E-04	3.707	1.920	10.02	28.09	0.1009E-04	3.51	
N041	0.1362E-04	3.769	1.951	10.13	28.12	0.7231E-05	3.51	
N042	0.1818E-04	3.629	1.907	9.88	28.05	0.8616E-05	3.51	
N043	0.1770E-04	3.792	1.935	10.17	28.13	0.8911E-05	3.51	
N044	0.2505E-04	3.550	1.893	9.74	28.02	0.1093E-04	3.51	
N045	0.2091E-04	3.772	1.931	10.14	28.12	0.1005E-04	3.51	
N046	0.1073E-04	3.747	1.927	10.09	28.11	0.5929E-05	3.51	
N047	0.1324E-04	3.870	1.948	10.31	28.16	0.8232E-05	3.51	
N048	0.1711E-04	4.037	1.976	10.61	28.24	0.1037E-04	3.51	
N049	0.2333E-04	3.950	1.961	10.45	28.20	0.1284E-04	3.51	
N050	0.1820E-04	4.139	1.992	10.79	28.28	0.1106E-04	3.51	
N051	0.1945E-04	4.064	1.980	10.66	28.27	0.1147E-04	3.51	
N052	0.1875E-04	4.112	1.988	10.74	28.25	0.1126E-04	3.51	
N053	0.1890E-04	4.158	1.995	10.82	28.29	0.1142E-04	3.51	
N054	0.1899E-04	4.062	1.980	10.65	28.25	0.1036E-04	3.51	
N055	0.1833E-04	4.025	1.985	10.71	28.26	0.1034E-04	3.51	
N056	0.2500E-04	3.994	1.968	10.53	28.22	0.1282E-04	3.51	
N060	0.1403E-04	4.208	2.003	10.91	28.31	0.7375E-05	3.51	
N061	0.1612E-04	4.360	2.027	11.17	28.38	0.8427E-05	3.51	
N062	0.1775E-04	4.313	2.020	11.09	28.36	0.9020E-05	3.51	

EXPERIMENTAL RESULTS

RUN NO.	KG COEFFICIENT (G.MCLE) ----- (ATM SEC SQCM)	AVERAGE VOLUME (CC)	EQUIVALENT DIAMETER (CM)	FRONTAL AREA (SQCM)	VELOCITY (CM/SEC)	HOLES TRANSFERRED (G.MDLES)	ECCENTRICITY
NO63	0.2032E-04	4.302	2.018	11.07	28.36	0.9991E-05	3.51
NO64	0.1935E-04	4.627	2.067	11.62	28.51	0.8869E-05	3.51
NO65	0.1610E-04	3.971	1.965	10.49	28.21	0.7897E-05	3.51
NO67	0.2096E-04	4.027	1.974	10.59	28.23	0.9761E-05	3.51
NO68	0.4141E-04	4.265	2.012	11.00	28.34	0.2343E-04	3.51
NO69	0.2149E-04	3.621	1.905	9.87	28.05	0.9222E-05	3.51
NO70	0.1030E-04	4.241	2.008	10.96	28.33	0.5710E-05	3.51
NO71	0.1516E-04	3.992	1.968	10.53	28.22	0.7557E-05	3.51
NO72	0.2072E-04	4.092	1.984	10.70	28.26	0.9787E-05	3.51
NO73	0.1796E-04	4.310	2.019	11.08	28.36	0.9098E-05	3.51
NO74	0.1763E-04	3.992	1.968	10.53	28.22	0.8508E-05	3.51
NO74	0.1577E-04	3.865	1.947	10.31	28.16	0.7625E-05	3.51
NO76	0.1777E-04	4.060	1.979	10.65	28.25	0.8662E-05	3.51
NO77	0.1927E-04	3.977	1.966	10.50	28.21	0.9087E-05	3.51
NO78	0.1903E-04	4.019	1.973	10.58	28.23	0.9065E-05	3.51
NO79	0.9268E-05	4.357	2.026	11.16	28.38	0.5307E-05	3.51
NO80	0.1700E-04	4.342	2.024	11.14	28.38	0.8760E-05	3.51
NO81	0.1702E-04	3.945	1.966	10.45	28.19	0.8208E-05	3.51
NO82	0.1736E-04	3.977	1.966	10.50	28.21	0.8382E-05	3.51
NO83	0.1523E-04	3.800	1.936	10.19	28.13	0.7330E-05	3.51
NO84	0.2557E-04	3.069	1.803	8.84	27.80	0.9254E-05	3.51
NO85	0.1662E-04	3.728	1.924	10.06	28.10	0.7751E-05	3.51
NO86	0.1663E-04	3.726	1.923	10.06	28.10	0.7752E-05	3.51
NO87	0.2647E-04	3.756	1.929	10.11	28.11	0.1099E-04	3.51
NO88	0.1613E-04	3.614	1.904	9.85	28.04	0.7430E-05	3.51
NO89	0.2013E-04	4.371	2.029	11.19	28.39	0.1003E-04	3.51
NO90	0.1970E-04	4.000	1.970	10.54	28.22	0.9275E-05	3.51
NO91	0.2157E-04	3.966	1.964	10.48	28.20	0.9865E-05	3.51
NO92	0.2192E-04	3.833	1.942	10.25	28.14	0.9746E-05	3.51
NO93	0.1534E-04	3.755	1.928	10.11	28.11	0.7312E-05	3.51

EXPERIMENTAL RESULTS

RUN NO.	KG COEFFICIENT (G. MOLE) ----- (ATM SEC SQCM)	AVERAGE VOLUME (CC)	EQUIVALENT DIAMETER (CM)	FRONTAL AREA (SQCM)	VELOCITY (CM/SEC)	MOLES TRANSFERRED (G. MOLES)	ECCENTRICITY
N094	0.2347E-04	3.864	1.947	10.30	28.16	0.1030E-04	3.51
N095	0.2244E-04	3.923	1.957	10.41	28.18	0.1008E-04	3.51
N096	0.1700E-04	3.908	1.954	10.38	28.18	0.8372E-05	3.51
N097	0.1546E-04	3.934	1.959	10.43	28.19	0.7596E-05	3.51
N098	0.2533E-04	3.863	1.947	10.30	28.16	0.1087E-04	3.51
N099	0.1783E-04	3.867	1.947	10.31	28.16	0.8394E-05	3.51
N100	0.1972E-04	3.822	1.940	10.23	28.14	0.8990E-05	3.51
N136	0.2226E-04	3.953	1.962	10.46	28.20	0.9797E-05	3.51
N137	0.1028E-04	4.059	1.979	10.65	28.25	0.5384E-05	3.51
N138	0.1666E-04	3.876	1.949	10.33	28.16	0.7755E-05	3.51
N139	0.1506E-04	3.996	1.969	10.54	28.22	0.7312E-05	3.51
N140	0.1900E-04	3.842	1.943	10.26	28.15	0.8531E-05	3.51
N141	0.1822E-04	3.681	1.950	10.33	28.17	0.8321E-05	3.51
N142	0.1835E-04	3.936	1.959	10.43	28.19	0.7723E-05	3.51
N143	0.1329E-04	3.963	1.963	10.48	28.20	0.6572E-05	3.51
N144	0.1671E-04	3.866	1.947	10.31	28.16	0.7761E-05	3.51
N145	0.1443E-04	4.127	1.990	10.76	28.28	0.7241E-05	3.51
N146	0.1938E-04	3.960	1.963	10.47	28.20	0.9846E-05	3.51
N147	0.1776E-04	3.402	1.866	9.47	27.95	0.7443E-05	3.51
N148	0.1637E-04	3.537	1.890	9.71	28.01	0.7181E-05	3.51
N149	0.1436E-04	3.403	1.866	9.47	27.95	0.6306E-05	3.51
N150	0.1608E-04	3.585	1.900	9.81	28.03	0.7153E-05	3.51
N151	0.1602E-04	3.679	1.915	9.97	28.07	0.7482E-05	3.51
N152	0.1602E-04	3.599	1.901	9.83	28.04	0.7147E-05	3.51
N153	0.1780E-04	3.673	1.914	9.90	28.07	0.7965E-05	3.51
N154	0.1529E-04	3.546	1.892	9.73	28.01	0.8691E-05	3.51
N155	0.1529E-04	3.739	1.926	10.08	28.10	0.7072E-05	3.51
N156	0.2125E-04	3.352	1.857	9.37	27.93	0.8417E-05	3.51
N157	0.2028E-04	3.227	1.833	9.14	27.87	0.7917E-05	3.51
N158	0.1906E-04	3.047	1.799	8.79	27.79	0.7256E-05	3.51

RUN NO.	EXPERIMENTAL RESULTS							MOLES TRANSFERRED	ECCENTRICITY
	KG COEFFICIENT (G.MOLE) ----- (ATM SEC SQCM)	AVERAGE VOLUME (CC)	EQUIVALENT DIAMETER (CM)	FRONTAL AREA (SQCM)	VELOCITY (CM/SEC)				
N159	0.2105E-04	2.976	1.785	8.66	27.75	0.7673E-05	3.51		
N160	0.2022E-04	3.235	1.835	9.15	27.87	0.7912E-05	3.51		
N161	0.1874E-04	3.002	1.790	8.71	27.77	0.7091E-05	3.51		
N162	0.1523E-04	3.335	1.854	9.34	27.92	0.6532E-05	3.51		
N163	0.1775E-04	3.224	1.833	9.13	27.87	0.7166E-05	3.51		
N164	0.1550E-04	3.199	1.828	9.08	27.86	0.6416E-05	3.51		
N165	0.1553E-04	2.907	1.771	8.52	27.72	0.6006E-05	3.51		
N166	0.1950E-04	3.415	1.968	9.49	27.95	0.8004E-05	3.51		
N167	0.2013E-04	2.919	1.773	8.55	27.73	0.7325E-05	3.51		
N168	0.1996E-04	2.698	1.727	8.11	27.63	0.6976E-05	3.51		
N169	0.1821E-04	2.813	1.751	8.34	27.68	0.6625E-05	3.51		
N170	0.1996E-04	2.619	1.710	7.95	27.59	0.6729E-05	3.51		
N171	0.1772E-04	2.702	1.728	8.12	27.63	0.6306E-05	3.51		
N172	0.1965E-04	2.261	1.629	7.21	27.43	0.5976E-05	3.51		
N173	0.2269E-04	2.737	1.735	8.19	27.65	0.7613E-05	3.51		
N174	0.1926E-04	2.774	1.743	8.26	27.66	0.6835E-05	3.51		

EXPERIMENTAL RESULTS

RUN NO.	KG COEFFICIENT (G. MOLE) ----- (ATM SEC SQCM)	AVERAGE VOLUME (CC)	EQUIVALENT DIAMETER (CM)	FRONTAL AREA (SQCM)	VELOCITY (CM/SEC)	MOLFS TRANSFERRED (G. MOLES)	ECCENTRICITY
HE31	0.2124E-04	4.190	2.000	10.87	28.31	0.9861E-05	3.51
HE32	0.1644E-04	3.763	1.930	10.12	28.11	0.7521E-05	3.51
HE33	0.1696E-04	4.143	1.993	10.79	28.28	0.8234E-05	3.51
HE34	0.1838E-04	4.151	1.994	10.81	28.29	0.8780E-05	3.51
HE35	0.2080E-04	4.093	1.985	10.71	28.26	0.9547E-05	3.51
HE36	0.2178E-04	3.783	1.933	10.16	28.12	0.9346E-05	3.51
HE37	0.2200E-04	3.754	1.928	10.11	28.11	0.9362E-05	3.51
HE38	0.2044E-04	3.482	1.881	9.61	27.98	0.8407E-05	3.51
HE39	0.2417E-04	3.636	1.908	9.89	28.05	0.9793E-05	3.51
HE40	0.2120E-04	3.784	1.933	10.16	28.12	0.9162E-05	3.51
HE41	0.2172E-04	3.166	1.822	9.02	27.84	0.8210E-05	3.51
HE42	0.2040E-04	3.245	1.837	9.17	27.88	0.7984E-05	3.51
HE43	0.1940E-04	3.048	1.799	8.80	27.79	0.7356E-05	3.51
HE44	0.2078E-04	2.812	1.751	8.34	27.68	0.7299E-05	3.51
HE45	0.1710E-04	2.755	1.739	8.22	27.65	0.6227E-05	3.51
HE46	0.2010E-04	4.116	1.988	10.75	28.27	0.9341E-05	3.51
HE47	0.1651E-04	4.221	2.005	10.93	28.32	0.8165E-05	3.51
HE48	0.1782E-04	3.965	1.964	10.48	28.20	0.8304E-05	3.51
HE49	0.1655E-04	3.915	1.955	10.39	28.18	0.7771E-05	3.51
HE50	0.2031E-04	3.995	1.969	10.53	28.22	0.9220E-05	3.51
HE51	0.1739E-04	2.774	1.743	8.26	27.66	0.6336E-05	3.51
HE52	0.1580E-04	3.276	1.843	9.23	27.89	0.6624E-05	3.51
HE53	0.2032E-04	3.078	1.805	8.25	27.80	0.7663E-05	3.51
HE54	0.2831E-04	2.295	1.634	7.26	27.44	0.7718E-05	3.51
HE55	0.1780E-04	2.979	1.785	8.55	27.76	0.6784E-05	3.51
HE56	0.2365E-04	2.882	1.766	8.47	27.71	0.8142E-05	3.51
HE57	0.1624E-04	3.681	1.916	9.97	28.07	0.7338E-05	3.51
HE58	0.1947E-04	3.182	1.825	9.05	27.95	0.7607E-05	3.51
HE59	0.1961E-04	3.247	1.837	9.18	27.88	0.7758E-05	3.51

EXPERIMENTAL RESULTS

RUN NO.	KG COEFFICIENT	AVERAGE VOLUME (CC)	EQUIVALENT DIAMETER (CM)	FRONTAL AREA (SQCM)	VELOCITY (CM/SEC)	MOLES TRANSFERRED (G.MOLES)	ECCENTRICITY
HE60	0.2347E-04	2.970	1.783	8.65	27.75	0.8281E-05	3.51

EXPERIMENTAL RESULTS

RUN NO.	KG COEFFICIENT (G. MOLE) (ATM SEC SQCM)		AVERAGE VOLUME (CC)	EQUIVALENT DIAMETER (CM)	FRONTAL AREA (SQCM)	VELOCITY (CM/SEC)	MOLES TRANSFERRED	ECCENTRICITY
FR001	0.1137	0.04	4.175	1.987	10.85	38.32	0.5578	3.51
FR002	0.1033	0.04	4.170	1.987	10.94	22.88	0.5574	3.51
FR003	0.0916	0.05	4.360	1.914	10.95	22.88	0.5551	3.51
FR004	0.0979	0.04	3.512	1.886	9.87	22.88	0.5478	3.51
FR005	0.1107	0.04	3.823	1.835	9.13	22.88	0.5400	3.51
FR006	0.1232	0.04	2.284	1.755	8.77	22.88	0.4832	3.51
FR007	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR008	0.1088	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR009	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR010	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR011	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR012	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR013	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR014	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR015	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR016	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR017	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR018	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51
FR019	0.1153	0.04	2.285	1.668	7.56	22.88	0.4637	3.51

2. Velocity and bubble Eccentricity

Table A2-2

<u>Photographic run number</u>	<u>Bubble volume (cc)</u>	<u>Eccentricity</u>	<u>Velocity (cm/sec)</u>	<u>Carrier gas</u>
4	4.12	3.47 3.37 <u>3.37</u> avg = 3.40	27.5	nitrogen
5	7.85	3.64 3.44 <u>3.44</u> avg = 3.51	30.0	nitrogen
8	3.07	3.88 3.63 <u>3.42</u> avg = 3.64	27.4	nitrogen
9	5.10	3.45 3.40 <u>3.63</u> avg = 3.49	27.8	Freon-14
10	6.23	3.52 <u>3.52</u> avg = 3.52	27.8 28.2	helium

3. K_G calculations

Due to the number of mass-transfer runs carried out and the variables involved, mass-transfer coefficients were calculated through a computer program.

A. Variables expressed as a function of temperature and bubble volume

(i) Density of benzene: The density of benzene was calculated from a temperature equation. The relationship was found to be linear over the temperature range $293 < T < 303^{\circ}\text{K}$.

$$\rho_B = 1.1868 - 0.00105(T)$$

where; ρ_B = density of benzene (g./ml)

T = absolute temperature ($^{\circ}\text{K}$)

Data for the density of benzene is given in appendix 1, table A1-3.

(ii) Vapor pressure of benzene: The vapor pressure of benzene was calculated from the following temperature dependent equation;

$$p^{\circ} = \frac{\exp (A + B/T)}{760.0}$$

where; p° = vapor pressure of benzene (atm)

T = absolute temperature ($^{\circ}\text{K}$)

A, B = constants

For $288.6 < T < 299.3$ °K,

$$A = 18.380$$

$$B = -4122.0$$

Data for the vapor pressure of benzene is given in appendix 1, table A1-5.

- (iii) Frontal surface area of spherical cap bubble: From theory, the frontal surface area of the spherical cap bubble was expressed in terms of the volume of the bubble and its eccentricity. For use with the integrated form of equation for K_G , the frontal surface area was expressed in terms of the average volume of the bubble over a specified interval.

$$A_F = \frac{\pi(E^2 + 4)}{\left(\frac{\pi}{3}\right)(3E^2 + 4)^{2/3}} \cdot \bar{V}^{2/3}$$

where; A_F = frontal surface area (cm²)
 E = eccentricity of bubble
 \bar{V} = average volume of bubble over interval (cc)

- (iv) Bubble rise velocity: The rise velocity of the bubble was expressed as a linear function of the volume of the bubble from figure 9a.

$$\bar{U} = 26.4 + 0.455(\bar{V})$$

where; \bar{U} = averaged velocity over interval (cm/sec)
 \bar{V} = average volume of bubble over interval (cc)

- (v) Eccentricity: The bubble eccentricities were found to be constant over the experimental volume range at a value of 3.51.

B. Volume of the bubble

The volume of the bubble at any of the reference levels in the column is calculated from the initial volume introduced under the spoon and the change in volume that has occurred after release.

- (i) Initial bubble volume: The initial volume of carrier gas in the bubble retainer was determined from the mercury travel in the capillary as noted from the adjacent scale (calibrated in cm).

$$V_1 = (\Delta \text{Hg})(x\text{AREA})$$

where; V_1 = initial volume of bubble (cc)

ΔHg = mercury travel (cm)

$x\text{AREA}$ = effective cross-sectional area of capillary
= cross-sectional area of capillary minus cross-sectional area of platinum wire
= 0.07368 (cm²)

- (ii) Volume change after release: The volume change of the bubble after release was determined by recording the varying voltage drop across the wire due to the mercury travel in the capillary. From the recorder calibration in appendix 7;

$$\Delta \text{Hg} = 23.2 (\Delta \text{mv})$$

where; Δmv = change in millivolts on recorder

and $\Delta V = (0.07368)(23.2)(\Delta mv)$

where; ΔV = volume change of bubble after release (cc)

(iii) Total volume of bubble: The volume of the bubble at any one of the reference levels in the column is given by;

$V = (0.07368)(\Delta Hg + 23.2 \Delta mv)$

where; V = total volume of bubble (cc)

C. Pressure within the bubble

Having evaluated the system lag, a volume could then be associated with any one of the reference levels in the column.

$z_1 = 220.0$ cm (spoon position)

$z_1, z_0 = 99.7$ cm (interface)

$z_2 = 84.4$ cm (6 inches above interface)

$z_3 = 69.0$ cm (12 inches above interface)

$z_4 = 38.3$ cm (24 inches above interface)

$z_5 = 6.0$ cm (top of column)

(1) Pressure in benzene layer: The pressure in the benzene layer is given by;

$P = (P_{ATM} + \rho_B(z)/\rho_M)/76.0$

where; P = total pressure in bubble (atm)

P_{ATM} = atmospheric pressure (cm Hg)

ρ_B = density of benzene (g./ml)

ρ_M = density of mercury (g./ml)

z = distance from datum level (cm)

(ii) Pressure in water layer: The pressure at any point in the water layer is given by;

$$P = (P_{ATM} + \rho_B(z_0)/\rho_M + \rho_W(z-z_0)/\rho_M)/76.0$$

where; P = total pressure (atm)

ρ_W = density of water (g./ml)

D. Sample calculation: MASS-TRANSFER RUN N174

Initial data: atmospheric pressure = 75.47 cm Hg
column temperature = 294.7 °K

Recorder trace data: Table A2-3

<u>Position</u>	<u>Trace value</u>
z ₁	0.9700
z ₁	0.7900
z ₂	0.6800
z ₃	0.5700
z ₄	0.5325
z ₅	0.5075

Program calculations: program nomenclature will be indicated in brackets after variable name

$$\begin{aligned}\rho_B \text{ (RHOB)} &= 1.1868 - 0.00105(294.7) \\ &= 1.1868 - 0.3094 \\ &= 0.8774 \text{ (g./ml)}\end{aligned}$$

$$\begin{aligned}p^0 \text{ (VAPL)} &= (\exp(18.380 - 4122.0/294.7))/760.0 \\ &= (\exp(18.380 - 13.9894))/760.0 \\ &= (\exp(4.3905))/760.0 \\ &= 80.6824/760.0 \\ &= 0.1061 \text{ (atm)}\end{aligned}$$

$$V_1 \text{ (VIN)} = (32.20)(0.07368) = 2.3725 \text{ (cc)}$$

$$\begin{aligned}V_0, V_1 \text{ (V0, VOL1)} &= 2.3725 + (0.9700 - 0.7900)(23.2)(0.07368) \\ &= 2.3725 + (0.1800)(1.7094) \\ &= 2.3725 + 0.3077 \\ &= 2.6802 \text{ (cc)}\end{aligned}$$

$$\begin{aligned}V_2 \text{ (VOL2)} &= 2.3725 + (0.9700 - 0.6800)(23.2)(0.07368) \\ &= 2.3725 + (0.2900)(1.7094) \\ &= 2.3725 + 0.4957 \\ &= 2.8682 \text{ (cc)}\end{aligned}$$

$$\begin{aligned}
 P_0, P_1 (P_0, PR1) &= (75.47 + (0.8774)(99.7)/(13.53))/76.0 \\
 &= (75.47 + 6.4654)/76.0 \\
 &= 81.935/76.0 \\
 &= 1.0781 \text{ (atm)}
 \end{aligned}$$

$$\begin{aligned}
 P_2 (PR2) &= (75.47 + (0.8774)(84.4)/(13.53))/76.0 \\
 &= (75.47 + 5.4732)/76.0 \\
 &= 80.943/76.0 \\
 &= 1.0651 \text{ (atm)}
 \end{aligned}$$

$$\begin{aligned}
 \bar{V} (\text{AVGVOL}) &= (2.6802 + 2.8682)/2.0 \\
 &= 2.7742 \text{ (cc)}
 \end{aligned}$$

$$\begin{aligned}
 A_F (\text{AREA}) &= \frac{(3.1416)(3.51^2 + 4.0)(2.7742)^{2/3}}{\left(\frac{(3.1416)(3.0(3.51^2 + 4.0))^{2/3}}{3.0}\right)} \\
 &= \frac{(3.1416)(16.32)(1.9750)}{(12.268)} \\
 &= 8.254 \text{ (cm}^2\text{)}
 \end{aligned}$$

$$\begin{aligned}
 \bar{U} (U) &= 26.4 + 0.455(2.7742) \\
 &= 26.4 + 1.235 \\
 &= 27.63 \text{ (cm/sec)}
 \end{aligned}$$

$$K_G (\text{COEFF}) = \frac{2.0(U)\rho_B}{1033.23 \text{ RTA}} \frac{P_2V_2 - P_1V_1}{(P_1 - P_2) \left(2p^0 + P_0V_0 \frac{(V_1 + V_2)}{V_1V_2} - (P_1 + P_2) \right)}$$

$$\begin{aligned}
 P_2V_2 - P_1V_1 &= (1.0650)(2.8682) - (1.0781)(2.6802) \\
 &= 3.0546 - 2.8895 \\
 &= 0.1651 \text{ (atm.cc)}
 \end{aligned}$$

$$\begin{aligned}
 &2p^0 + P_0V_0 \frac{(V_2 + V_1)}{V_2V_1} - (P_1 + P_2) \\
 &= 2.0(0.1061) + (1.0781)(2.6802) \frac{(2.6802 + 2.8682)}{(2.6802)(2.8682)} - (1.0781 + 1.065) \\
 &= 0.2122 + 2.8895 \frac{(5.5484)}{(7.6873)} - (2.1431) \\
 &= 0.2122 + 2.8895(0.7218) - (2.1431) \\
 &= 0.2122 + 2.0855 - 2.1431 \\
 &= 0.1546 \text{ (atm)}
 \end{aligned}$$

$$(P_1 - P_2) = 1.0781 - 1.0650 = 0.0131 \text{ (atm)}$$

$$K_G = \frac{(2.0)(27.63)(0.8774)}{(1033.23)(82.06)(294.7)(8.254)} \cdot \frac{0.1651}{(0.0131)(0.1546)}$$
$$= \frac{48.492}{2.0621 \times 10^8} \cdot \frac{0.1651}{0.002025}$$
$$= 23.5158 \times 10^{-8} \cdot 81.53$$
$$K_G = 1.917 \times 10^{-5} \text{ or } 0.192 \text{ E-04 (g.mole/sq cm sec atm)}$$

The sample calculation is accompanied by its corresponding computer printout on the following page.

APPENDIX 3.

THEORETICAL

1. Evaluation of K_G
2. Surface area of spherical cap bubble
3. Bubble volume

1. Equation for the calculation of K_G

The rate of mass transfer for a pure liquid evaporating into an inert carrier gas is given by;

$$\frac{dn}{d\theta} = K_G A (p^* - p_b) \quad (1.1)$$

assuming that the bulk of the carrier gas is perfectly mixed and noting that;

$$p^* = p^0 \quad (1.2)$$

and
$$p_b = yP \quad (1.3)$$

substituting (1.3) and (1.2) into (1.1);

$$\frac{dn}{d\theta} = K_G A (p^0 - yP) \quad (1.4)$$

or
$$\frac{dn}{d\theta} = K_G A \left(\frac{p^0}{P} - y \right) P \quad (1.5)$$

assuming isothermal conditions;

$$y = \frac{PV/RT - P_0V_0/RT}{PV/RT} \quad (1.6)$$

or
$$y = \frac{PV - P_0V_0}{PV} \quad (1.7)$$

substituting (1.7) into (1.5);

$$\frac{dn}{d\theta} = K_G A \left(\frac{p^0}{P} - \left(\frac{PV - P_0V_0}{PV} \right) \right) P \quad (1.8)$$

or
$$\frac{dn}{d\theta} = K_G A \left(p^0 - \left(\frac{PV - P_0V_0}{V} \right) \right) \quad (1.9)$$

$$\text{or } \frac{dn}{d\theta} = K_G A (p^0 - P + \frac{P_0 V_0}{V}) \quad (1.10)$$

Bubble velocity:

$$\text{from } P = \frac{\rho g H}{g_0} \quad (1.11)$$

$$\frac{dP}{d\theta} = \frac{\rho g}{g_0} \frac{dH}{d\theta} \quad (1.12)$$

then the bubble velocity is given by;

$$U = \frac{-dH}{d\theta}$$

$$\text{and } U = \frac{-g_0}{\rho g} \frac{dP}{d\theta} \quad (1.14)$$

expressing the mass-transfer rate in terms of the ideal gas law;

$$\frac{dn}{d\theta} = \frac{1}{RT} \left(\frac{PdV}{d\theta} + \frac{VdP}{d\theta} \right) \quad (1.15)$$

and from the chain rule;

$$\frac{dP}{d\theta} = \frac{dV}{d\theta} \cdot \frac{dP}{dV} \quad (1.16)$$

$$\text{from (1.14)} \quad \frac{dP}{d\theta} = \frac{-U \rho g}{g_0} \quad (1.17)$$

combining (1.17) and (1.16) to eliminate $dP/d\theta$

$$\frac{dV}{d\theta} = \frac{-U \rho g}{g_0} \frac{dV}{dP} \quad (1.18)$$

replacing (1.17) and (1.18) in (1.15);

$$\frac{dn}{d\theta} = \frac{-U_0 g}{g_0 RT} \left(\frac{PdV}{dP} + V \right) \quad (1.19)$$

equating (1.19) with (1.10);

$$\frac{-U_0 g}{RT g_0} \left(\frac{PdV}{dP} + V \right) = K_G A \left(p^0 - P + \frac{P_0 V_0}{V} \right) \quad (1.20)$$

multiplying (1.20) by dP and $\frac{-g_0 RT}{U_0 g}$

$$PdV + VdP = \frac{-g_0 RT K_G A}{U_0 g} \left(p^0 - P + \frac{P_0 V_0}{V} \right) dP \quad (1.21)$$

integrating (1.21) over a small interval from 1 to 2;

$$\int_1^2 d(PV) = \frac{-g_0 RT K_G A}{U_0 g} \int_1^2 \left(p^0 - P + \frac{P_0 V_0}{V} \right) dP \quad (1.22)$$

$$P_2 V_2 - P_1 V_1 = \frac{-g_0 RT A K_G}{U_0 g} \left(p^0 (P_2 - P_1) - (P_2^2 - P_1^2) + \int_1^2 \frac{P_0 V_0}{V} dP \right) \quad (1.23)$$

using the trapezoidal rule to approximate the last integral in equation (1.23);

$$P_0 V_0 \int_1^2 \frac{dP}{V} = \frac{P_0 V_0}{2} \left(\frac{V_2 + V_1}{V_2 V_1} \right) (P_2 - P_1) \quad (1.24)$$

$$\text{and changing sign by } -(P_1 - P_2) = (P_2 - P_1) \quad (1.25)$$

$$P_2 V_2 - P_1 V_1 = \frac{g_0 RT A K_G}{2 U_0 g} \left((P_1 - P_2) (2p^0 + P_0 V_0 \left(\frac{V_2 + V_1}{V_2 V_1} \right)) - (P_2^2 - P_1^2) \right) \quad (1.26)$$

solving (1.26) for K_G ;

$$K_G = \frac{2U\rho}{1033.23 \text{ RTA}} \cdot \frac{P_2 V_2 - P_1 V_1}{(P_1 - P_2) \left(2P_0 V_0 \left(\frac{V_2 + V_1}{V_2 V_1} \right) - (P_2 + P_1) \right)}$$

(1.27)

where;

$$g = 980.6 \text{ (cm/sec}^2\text{)}$$

$$g_0 = 1.01325 \times 10^6 \text{ (dynes/cm}^2 \text{ atm)}$$

$$\frac{g}{g_0} = 1/1033.23$$

2. Frontal surface area of a spherical cap bubble

(2.a) Volume of a spherical cap bubble from a solid of revolution

from a solid of revolution in reference to figure 1a;

$$V = \int_a^b dV = \pi \int_{r \cos \theta}^r y^2 dx \quad (2.1)$$

and from; $x^2 - y^2 = r^2$ we have; (2.2)

$$y^2 = r^2 - x^2 \quad (2.3)$$

replacing y^2 in (2.1) by (2.3);

$$V = \pi \int_{r \cos \theta}^r (r^2 - x^2) dx \quad (2.4)$$

integrating (2.4);

$$V = \pi \left(\int_{r \cos \theta}^r r^2 dx - \int_{r \cos \theta}^r x^2 dx \right) \quad (2.5)$$

or $V = \pi(r^3 - r^3 \cos \theta - \frac{1}{3}(r^3 - r^3 \cos^3 \theta))$ (2.6)

or $V = \frac{\pi r^3}{3} (2 + \cos^3 \theta - 3 \cos \theta)$ (2.7)

(2.b) Surface area (frontal) of a spherical cap bubble

the surface area may be found from;

$$S_x = 2\pi \int_a^b y \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx \quad (2.8)$$

where; $b = r$

$$a = r \cos \theta$$

$$y = (r^2 - x^2)^{1/2} \quad (2.9)$$

$$\frac{dy}{dx} = -(r^2 - x^2)^{-1/2} x \quad (2.10)$$

$$\frac{dy}{dx} = x^2 (r^2 - x^2) \quad (2.11)$$

substituting (2.9) and (2.11) in (2.8)

$$S_x = 2\pi \int_{r \cos \theta}^r (r^2 - x^2)^{1/2} (1 + (r^2 - x^2)^{-1} x^2)^{1/2} dx \quad (2.12)$$

$$S_x = 2\pi \int_{r \cos \theta}^r r dx \quad (2.13)$$

$$\text{from which; } S_x = 2\pi r^2 (1 - \cos \theta) \quad (2.14)$$

solving for r in (2.7) and substituting the result in (2.14) and noting that $A_F = S_x$;

$$A_F = \frac{2\pi(1 - \cos \theta) v^{2/3}}{\left(\pi\left(\frac{2}{3} - \cos \theta + \frac{\cos^3 \theta}{3}\right)\right)^{2/3}} \quad (2.15)$$

(2.c) Relationship of the Eccentricity of a spherical cap to $\cos\theta$

in reference to figure 1b, we have;

$$\cos\theta = \frac{r-b}{b} \quad (2.16)$$

and noting that; $r^2 = (r-b)^2 + (a/2)^2$ (2.17)

or; $r = \frac{4b^2 + a^2}{8b}$ (2.18)

replacing (2.18) in (2.16);

$$\cos\theta = \frac{(4b^2 + a^2)/8b - b}{(4b^2 + a^2)/8b} \quad (2.19)$$

simplifying; $\cos\theta = \frac{a^2/b^2 - 4}{a^2/b^2 - 4}$ (2.20)

noting that; $E = a/b$ (2.21)

$$\cos\theta = \frac{E^2 - 4}{E^2 + 4} \quad (2.22)$$

substituting (2.22) into (2.15) to eliminate $\cos\theta$;

$$A_F = \frac{\pi(E^2+4) \cdot V^{2/3}}{\left(\frac{\pi}{3}\right)(3E^2+4)^{2/3}} \quad (2.23)$$

3. Relationship of volume of a spherical cap bubble to its width and Eccentricity

In reference to figure 1b and integrating equation (2.4) between the limits (r-b) to (b);

$$V = \pi(rb^2 - \frac{b^3}{3}) \quad (3.1)$$

substituting equation (2.18) into (3.1);

$$V = \pi a^3 \left(\frac{b}{8a} + \frac{b^3}{6a^3} \right) \quad (3.2)$$

now substituting $a_s = a/2$ and $E = a/b$ into (3.2);

$$V = \frac{a^3}{3E} \left(3 + \frac{4}{E^2} \right) \quad (3.3)$$

or
$$V = \frac{a^3}{24E} \left(3 + \frac{4}{E^2} \right) \quad (3.4)$$

APPENDIX 4.

DIFFUSIVITY OF BENZENE INTO DIFFERENT CARRIER GASES

The diffusivity of benzene into different carrier gases was calculated from the Wilke-Lee modification of the Hirschfelder-Bird-Spotz equation (9). The equation is given below;

$$D_{AB} = \frac{(0.00107 - 0.000246 \sqrt{\frac{1}{M_A} + \frac{1}{M_B}}) T^{3/2} (\sqrt{\frac{1}{M_A} + \frac{1}{M_B}})}{P_t (r_{AB})^2 (f(kT/e_{AB}))}$$

- where;
- D_{AB} = diffusivity (cm²/sec)
 - T = absolute temperature (°K)
 - P_t = total pressure (atm)
 - r_{AB} = molecular separation at collision Å
= $(r_A + r_B)/2$
 - e_{AB} = energy of molecular interaction (ergs)
= $(e_A e_B)^{1/2}$
 - k = Boltzmann's constant
 - $f(kT/e_{AB})$ = collision function

Table A4-1

<u>Carrier gas</u>	<u>Diffusivity of benzene</u> (sq cm/sec)
nitrogen	0.097
oxygen	0.091
methane	0.104
helium	0.373
neon	0.155
argon	0.083
hydrogen	0.376
Freon-14	0.056
xenon	0.055

Where e/k or r are not directly available, they may be estimated from the following relationships (9);

$$r = 1.18(v)^{1/3}$$

$$e/k = 1.21 T_b$$

where; v = molecular volume = sum of atomic volumes

T_b = normal boiling point ($^{\circ}K$)

Sample calculation: BENZENE-NITROGEN SYSTEM

A = benzene
B = nitrogen

$$P_t = 1.0 \text{ (atm)}$$

$$T = 298.15 \text{ (}^{\circ}K\text{)}$$

$$r_A = 5.392 \quad e_A/k = 427.43 = 1.21(80.1-273.15)$$

$$r_B = 3.681 \quad e_B/k = 91.46$$

$$r_{AB} = 4.537 \quad e_{AB}/k = 197.72$$

$$M_A = 78.114 \quad M_B = 28.014$$

$$kT/e_{AB} = 1.508 \quad f(kT/e_{AB}) = 0.6 \quad (9)$$

$$\left(\frac{1}{M_A} + \frac{1}{M_B}\right)^{1/2} = 0.2202$$

$$D_{AB} = \frac{(0.00107 - 0.000246(0.2202))(298.15)^{3/2}(0.2202)}{(1.0)(4.537)^2(0.6)}$$

$$D_{AB} = 0.097 \text{ (sq cm/sec)}$$

APPENDIX 5.

SYSTEM LAG DETERMINATION: METHOD 2
COMPARISON OF METHOD 1 AND METHOD 2

The calculations involved in the procedures of method 2 for the location of the interface are given below.

SAMPLE CALCULATION: mass-transfer run N138

The volume of the bubble at the interface is calculated on the assumption of a saturated bubble initially under the spoon. The volume of the bubble at the interface is then the initial volume multiplied by the pressure ratio of the inverter and interface levels.

Pressure at the inverting spoon = 1.195 (atm)

Pressure at the interface = 1.078 (atm)

Initial volume (in spoon) = (0.07368)(46.0) = 3.389 (cc)

Interface volume (3.389)(1.195)/(1.078) = 3.757 (cc)

$$\begin{aligned} \text{Interface position on recorder trace} &= \text{initial recorder trace value} - \frac{\text{interface volume} - \text{inverter volume}}{(23.2)(0.07368)} \\ &= 0.9800 - \frac{(3.757-3.389)}{(23.2)(0.07368)} \\ &= 0.7648 \end{aligned}$$

Table A5-1

<u>Method</u>	<u>Interface position recorder trace</u>	<u>Volume at interface (cc)</u>
1	0.7600	3.757
2	0.7648	3.765

Table A5-2 compares the interface positions determined from visual inspection of the recorder trace (method 1) and from back-calculations (method 2) for runs N136 to N174.

Figure 16 indicates the approach to saturation of the spherical cap bubbles for the nitrogen-benzene system.

TABLE A5-2

NITROGEN BENZENE JAN. 25, 1971 N136-N174

CAPILLARY SIZE=0.1210 INCHES

RUN NO.	RECORDER INITIAL	RECORDER INTERFACE	METHOD 2 INTERFACE	VOLUME AT METHOD 1 & 2	INTERFACE METHOD 2	FINAL VOLUME	SATURATED VOLUME
N136	0.9959	0.7825	0.7756	81.88	306	58.01	4.6153
N137	0.9475	0.6900	0.7222	97.31	891.57	61.08	4.8018
N138	0.9800	0.7650	0.7564	76.54	715.41	170.2	4.5506
N139	0.9800	0.7700	0.7523	82.23	904.5	236	4.7088
N140	0.9800	0.7750	0.7595	76.31	722.0	33	4.4980
N141	0.9800	0.7650	0.7689	82.42	851.4	114	4.5220
N142	0.9825	0.7800	0.7687	85.44	773.7	14	4.6537
N143	0.9825	0.7800	0.7547	85.44	777.6	59	4.5779
N144	0.9550	0.7225	0.7320	0.36	88.56	6	4.3366
N145	0.9600	0.7700	0.7720	29.74	244.9	58	4.1503
N146	0.9725	0.7775	0.7890	31.62	291.9	7	4.2137
N147	0.9850	0.7700	0.7819	31.62	252.0	18	4.1377
N148	0.9850	0.7700	0.7619	45.26	455.9	4	4.3247
N149	0.9800	0.7650	0.7772	50.8	540.6	5	4.4054
N150	0.9825	0.7625	0.7749	60.8	600.5	20	4.3145
N151	0.9600	0.7450	0.7691	67.8	646.4	5	4.3952
N152	0.9550	0.7575	0.7835	77.8	707.8	20	4.3528
N153	0.9500	0.7625	0.8220	82.2	846.4	10	4.3760
N154	0.9875	0.8075	0.8205	98.2	941.8	4	4.5784
N155	0.9500	0.7700	0.7930	103.0	1015.3	0	4.5095
N156	0.9750	0.7675	0.7870	124.0	1240.0	17	4.7784
N157	0.9750	0.7675	0.7870	140.0	1400.0	6	4.5170
N158	0.9650	0.7675	0.7870	124.0	1240.0	7	4.5975
N159	0.9500	0.7675	0.7870	140.0	1400.0	6	4.5170
N160	0.9750	0.7675	0.7870	140.0	1400.0	6	4.5975
N161	0.9650	0.7675	0.7870	140.0	1400.0	6	4.5170
N162	0.9650	0.7675	0.7870	140.0	1400.0	6	4.5975
N163	0.9650	0.7675	0.7870	140.0	1400.0	6	4.5170

7557
4149
4064
1470
1847
5959
4362
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7058
3710
3134
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2222
1333
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3333

1037
3824
2208
2219
4444
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1075
2338
3184
1444
5145
2276
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7675
7825
7255
7025
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7879
8162
8129
8490
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8194
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8194

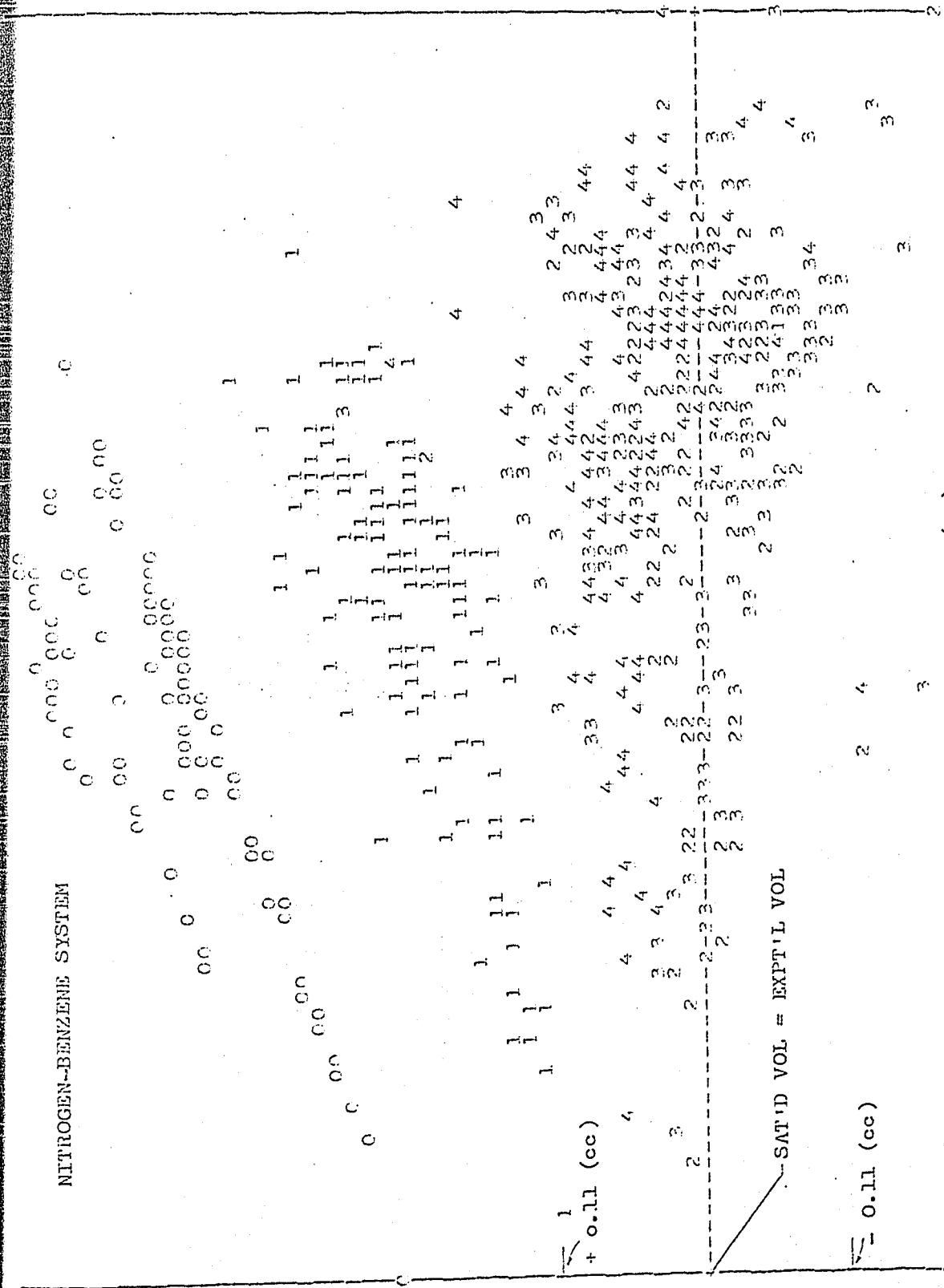
7675
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9475
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N164
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N173
N174

NITROGEN-BENZENE SYSTEM

(SATURATED-EXPERIMENTAL) VOLUME (cc)



EXPERIMENTAL VOLUME (cc)

FIGURE 16b

1 = 0.2185 G1
2 = 0.5405 G1

APPENDIX 6.

EQUIPMENT SPECIFICATIONS

Volume measurement equipment

Chart recorder:

Manufacturer: Bausch and Lomb

Model: VOM 7

Specifications:

full scale spans: millivolts (dc)
0.5, 1.0, 10, 100

volts (dc)
1, 10

microamperes (dc)
1, 10, 100

milliamperes (dc)
1, 10

ohms
1, 10, 100, 1000, 10K,
100K

chart speeds: 20 in/min, 5 in/min, 1 in/min,
0.2 in/min, 0.05 in/min

response time: less than 0.5 sec on all
ranges

sensitivity: $\pm 0.25\%$ or less of full scale

accuracy: for the 0.5, 1.0, 10.0, mv
scales, $\pm 0.5\%$ of full scale

event marker: 250 ma at 6 volts dc

VTVM (vacuum tube voltmeter):

Manufacturer: Hewlett-Packard

Model: 410c

Specifications:

dc voltmeter ± 15 mv to ± 1500 v

dc ammeter $\pm 1.5\mu$ a to ± 150 ma

accuracy: $\pm 3\%$ of full scale

ohmmeter: 10Ω to 10 megohms

DC power supply:

Manufacturer: Hewlett-Packard

Model: 6218A

Specifications:

output: 0-50 volts dc

0-200 ma

Photographic equipment

HYCAM camera:

Manufacturer: Red Lake Laboratories Inc.
Model: K20SIAR
Specifications:

16mm (1/2 frame), variable frame rate controlled by external power supply, maximum frame rate of 18,000 pictures per second, provision for timing light generator for accurate frame rate determination

Lenses: Comiscar television lens, 75mm, No. 14714, f stop 1.4 to 22, focusing 2.0 ft. to infinity

Comiscar television lens, 25mm, No. 38157, f stop 1.4 to 22, focusing 2.0 ft. to infinity

Timing light generator:

Manufacturer: Red Lake Laboratories Inc.
Model: TLG 3
Specifications:

frequency of 10, 100 or 1000 cycles/second

Lighting:

Manufacturer: Berkey-Colortran
Model: LCQ-II
Specifications:

2 required, 1000 watts at 120 volts and 8.3 amperes

Transformer 'powerstat':

Manufacturer: Superior Electric Co.
Specifications:

240 volt inlet, 0-300 volts outlet

Light meter:

Manufacturer: Ashi Pentax
Model: Spotmeter III
Specifications:

ASA range: 6-600

Shutter speed range: 4 min - 1/4000 sec

Film:

Manufacturer: Kodak
Specifications:

Type 4-X reversal 7277 for 16mm high speed
cameras, 100 ft., ASA 320-400

Projector:

Manufacturer: L-W Photo Inc.
Model: 900B 'motion analyzer'
Specifications:

Provision for viewing one frame at a time,
16-24 frames/second viewing speeds, forward
or reverse operation

APPENDIX 7.

CHART RECORDER CALIBRATION

By introducing increased amounts of carrier gas into the bubble retainer, the voltage drop across the remaining exposed platinum wire was noted along with the mercury travel in the capillary. The calibration curve of mercury travel (cm) versus the voltage drop across the wire (millivolts) was found to be a straight line with a slope of 23.2. A potentiometer was used to accurately measure the voltage drop across the platinum wire. The calibration curve is given in figure 17 for data taken on two separate occasions.

Table A7-1

Curve 1 (January 19, 1971)

<u>Mercury travel(cm)</u>	<u>Potentiometer (mv)</u>
0.0	3.998
10.6	3.607
18.9	3.267
27.4	2.905
35.45	2.560
41.40	2.305
53.65	1.770
58.25	1.570
63.10	1.362
66.70	1.204
67.20	1.186

the data
exposed
in the
cm (mo)
was found
potential
of each
Figure 17

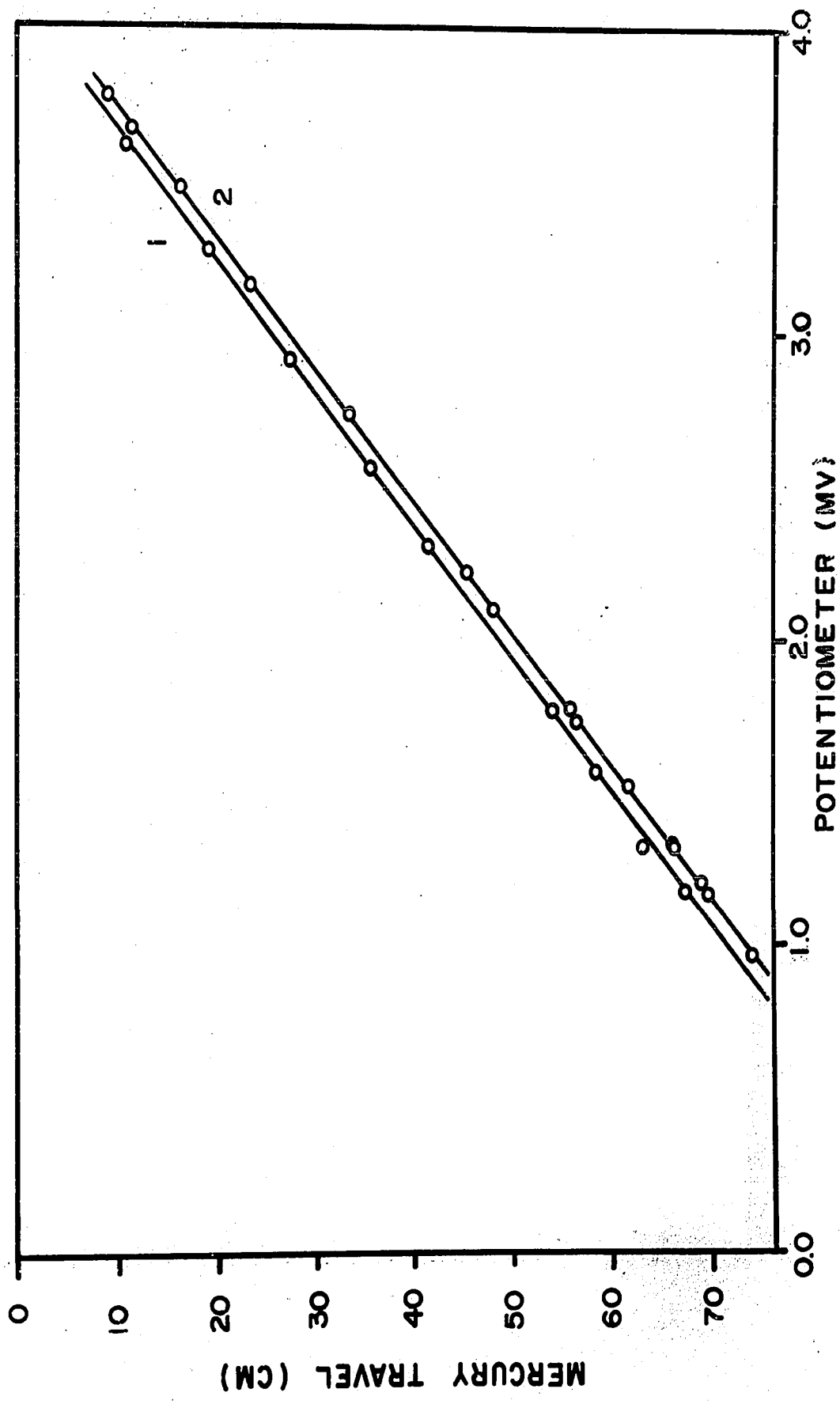


FIGURE 17

Table A7-2

Curve 2 (December 10, 1970)

<u>Mercury travel</u> (cm)	<u>Potentiometer</u> (mv)	<u>Recorder</u> (mv)
0.0	4.060	
8.90	3.775	
16.10	3.475	
23.35	3.160	
33.50	2.740	2.55
45.20	2.225	2.05
55.55	1.783	1.60
61.60	1.520	1.30
69.10	1.203	0.90
47.80	2.100	1.90
56.20	1.740	1.50
65.90	1.325	1.15
66.20	1.313	1.15
69.70	1.1650	1.00
74.20	0.9675	0.95
74.75	0.9450	0.92
78.30	0.7925	0.78
83.10	0.5875	0.57
11.30	3.6375	

0.0000
10)

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0.79
0.80
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0.83
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0.85
0.86
0.87
0.88
0.89
0.90
0.91
0.92
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1.00

APPENDIX 8.

CURVE FITTING DATA
(K_G vs BUBBLE VOLUME)



TABLE A8-1
 POLYNOMIAL IS OF DEGREE 1 BASED ON 135 DATA POINTS FOR NITROGEN - BENZENE SYSTEM

THE POLYNOMIAL COEFFICIENTS ARE

A(0) = 0.0000221

A(1) = -0.0000008

POINT	X, EXPERIMENTAL	Y, EXPERIMENTAL	Y, CALCULATED	YEXPT-YCALC	PERCENT ERROR
1	4.0784807	0.0000154	0.0000187	-0.0000033	-17.736
2	4.0913010	0.0000193	0.0000187	0.0000006	3.329
3	4.0179157	0.0000243	0.0000188	0.0000056	29.589
4	4.0543744	0.0000160	0.0000187	-0.0000027	-14.615
5	3.9751072	0.0000196	0.0000188	0.0000008	4.464
6	3.9885169	0.0000256	0.0000188	0.0000068	35.955
7	4.1411085	0.0000209	0.0000187	0.0000023	12.174
8	3.8424835	0.0000280	0.0000189	0.0000091	48.017
9	4.3073292	0.0000158	0.0000185	-0.0000028	-14.897
10	4.0737648	0.0000179	0.0000187	-0.0000008	-4.243
11	3.5582991	0.0000258	0.0000191	0.0000066	34.505
12	4.0692692	0.0000184	0.0000187	-0.0000003	-1.763
13	4.1176043	0.0000209	0.0000187	0.0000022	11.629
14	4.3006992	0.0000240	0.0000185	0.0000054	29.215
15	4.3209610	0.0000197	0.0000185	0.0000011	6.103
16	4.2709322	0.0000204	0.0000186	0.0000018	9.817
17	4.1179724	0.0000223	0.0000187	0.0000036	19.309
18	3.5127659	0.0000177	0.0000192	-0.0000014	-7.507
19	3.4742308	0.0000185	0.0000192	-0.0000008	-3.961
20	3.5999289	0.0000134	0.0000191	-0.0000057	-29.746
21	3.5753202	0.0000187	0.0000191	-0.0000004	-2.053
22	3.4807138	0.0000140	0.0000192	-0.0000052	-27.248
23	3.1789217	0.0000277	0.0000195	0.0000082	42.320
24	4.0059061	0.0000188	0.0000188	0.0000000	0.165
25	3.3784456	0.0000233	0.0000193	0.0000040	20.570
26	3.1500473	0.0000141	0.0000194	-0.0000053	-27.269
27	3.1339025	0.0000238	0.0000195	0.0000044	22.334
28	3.8149261	0.0000161	0.0000189	-0.0000028	-14.978

29	3.7297207	0.0000174	0.0000190	-0.0000017	-5.793
30	3.6148119	0.0000256	0.0000191	0.0000075	39.271
31	3.8413038	0.0000218	0.0000189	0.0000029	15.287
32	3.6565961	0.0000269	0.0000190	0.0000078	41.205
33	3.9154263	0.0000213	0.0000189	0.0000024	12.970
34	3.6809025	0.0000255	0.0000190	0.0000064	33.721
35	3.7815495	0.0000246	0.0000190	0.0000056	29.743
36	3.7520781	0.0000269	0.0000190	0.0000079	41.537
37	3.7858538	0.0000136	0.0000190	-0.0000054	-28.336
38	3.8435144	0.0000184	0.0000189	-0.0000005	-2.811
39	3.6488523	0.0000156	0.0000191	-0.0000035	-18.321
40	3.7069120	0.0000214	0.0000190	0.0000024	12.404
41	3.7694664	0.0000136	0.0000190	-0.0000054	-23.247
42	3.6290321	0.0000182	0.0000191	-0.0000009	-4.764
43	3.7517919	0.0000177	0.0000190	-0.0000013	-6.632
44	3.5504160	0.0000250	0.0000192	0.0000059	30.775
45	3.7723398	0.0000209	0.0000190	0.0000019	10.222
46	3.7474365	0.0000167	0.0000189	-0.0000083	-43.495
47	3.8656718	0.0000132	0.0000189	-0.0000057	-29.908
48	4.0372190	0.0000171	0.0000188	-0.0000016	-8.769
49	3.9496136	0.0000233	0.0000188	0.0000045	23.890
50	4.1386032	0.0000182	0.0000187	-0.0000005	-2.558
51	4.0640392	0.0000194	0.0000187	0.0000007	3.731
52	4.1117086	0.0000187	0.0000187	0.0000001	0.280
53	4.1580544	0.0000189	0.0000187	0.0000002	1.322
54	4.0619764	0.0000170	0.0000187	-0.0000017	-9.333
55	4.0548372	0.0000168	0.0000187	-0.0000019	-10.068
56	3.9939690	0.0000230	0.0000188	0.0000042	22.401
57	4.2080832	0.0000141	0.0000186	-0.0000045	-24.396
58	4.3604545	0.0000161	0.0000185	-0.0000024	-12.809
59	4.3127823	0.0000177	0.0000185	-0.0000008	-4.231
60	4.3020992	0.0000203	0.0000185	0.0000018	9.622
61	4.6271000	0.0000193	0.0000183	-0.0000019	-10.548
62	3.9708328	0.0000151	0.0000188	-0.0000027	-14.388
63	4.0265360	0.0000210	0.0000188	0.0000022	11.682
64	4.2648172	0.0000414	0.0000186	0.0000228	122.971
65	3.6210012	0.0000215	0.0000191	0.0000024	12.510

103	3.9355412	0.0000153	0.0000138	-0.0000025	-13.216
104	3.9625082	0.0000133	0.0000188	-0.0000055	-29.349
105	3.8655453	0.0000167	0.0000189	-0.0000022	-11.552
106	4.1266670	0.0000145	0.0000187	-0.0000042	-22.497
107	3.9601498	0.0000194	0.0000188	0.0000006	2.997
108	3.4024658	0.0000178	0.0000193	-0.0000015	-7.832
109	3.5366383	0.0000164	0.0000192	-0.0000028	-14.564
110	3.4030552	0.0000144	0.0000193	-0.0000049	-25.472
111	3.5888033	0.0000161	0.0000191	-0.0000030	-15.905
112	3.6794300	0.0000167	0.0000190	-0.0000024	-12.522
113	3.5585704	0.0000160	0.0000191	-0.0000031	-16.162
114	3.6726503	0.0000178	0.0000191	-0.0000013	-6.569
115	3.5456257	0.0000210	0.0000192	0.0000019	9.701
116	3.7394047	0.0000153	0.0000190	-0.0000037	-19.530
117	3.3519486	0.0000213	0.0000193	0.0000019	10.018
118	3.2268124	0.0000203	0.0000194	-0.0000009	4.462
119	3.0465918	0.0000191	0.0000196	-0.0000005	-2.575
120	2.9758587	0.0000211	0.0000196	0.0000014	7.289
121	3.2353592	0.0000202	0.0000194	0.0000008	4.148
122	3.0021629	0.0000187	0.0000196	-0.0000009	-4.383
123	3.3350496	0.0000153	0.0000193	-0.0000040	-20.925
124	3.2244549	0.0000177	0.0000194	-0.0000017	-8.620
125	3.1594047	0.0000155	0.0000194	-0.0000039	-20.265
126	2.9065266	0.0000155	0.0000197	-0.0000042	-21.099
127	3.4149189	0.0000195	0.0000193	0.0000002	1.201
128	2.5189777	0.0000201	0.0000197	0.0000005	2.352
129	2.6594539	0.0000200	0.0000198	0.0000001	0.535
130	2.8133211	0.0000152	0.0000198	-0.0000015	-7.826
131	2.6193953	0.0000200	0.0000199	-0.0000000	0.217
132	2.7022114	0.0000177	0.0000198	-0.0000021	-10.723
133	2.2613840	0.0000196	0.0000202	-0.0000006	-2.773
134	2.7357678	0.0000227	0.0000198	0.0000029	14.478
135	2.7741966	0.0000193	0.0000198	-0.0000005	-2.583

ERROR CRITERION

SUM OF SQUARES CF DELTAY IS 0.2353412E-08

MEAN SQUARE DEVIATION IS 0.1744116E-10

Table A8 - 2

POLYNOMIALS OF DEGREE 1 BASED ON 30 DATA POINTS
 THE POLYNOMIAL COEFFICIENTS ARE

A(C) = C.C000262
 A(I) = -C.C000018

POINT	X, EXPERIMENTAL	Y, EXPERIMENTAL	Y, CALCULATED	YEXPT-YCALC	PERCENT ERROR
1	4.190000	212	0.000000	0.000000	14.361
2	3.762662	170	0.000000	0.000000	15.072
3	4.151477	184	0.000000	0.000000	-1.144
4	3.082000	88	0.000000	0.000000	1.415
5	3.753611	204	0.000000	0.000000	1.883
6	3.753611	204	0.000000	0.000000	1.237
7	3.683238	42	0.000000	0.000000	2.565
8	3.753611	42	0.000000	0.000000	1.404
9	3.358803	217	0.000000	0.000000	2.732
10	3.247215	44	0.000000	0.000000	3.263
11	3.247215	48	0.000000	0.000000	6.082
12	3.712537	108	0.000000	0.000000	-1.434
13	3.712537	108	0.000000	0.000000	1.306
14	3.205018	15	0.000000	0.000000	1.404
15	3.205018	15	0.000000	0.000000	1.688
16	3.265018	63	0.000000	0.000000	1.268
17	3.265018	63	0.000000	0.000000	1.820
18	3.277544	27	0.000000	0.000000	1.912
19	3.277544	27	0.000000	0.000000	1.386
20	3.278502	22	0.000000	0.000000	2.377
21	3.278502	22	0.000000	0.000000	1.444
22	3.278502	22	0.000000	0.000000	1.710
23	3.278502	22	0.000000	0.000000	1.386
24	3.278502	22	0.000000	0.000000	1.377
25	3.278502	22	0.000000	0.000000	1.444
26	3.278502	22	0.000000	0.000000	1.377
27	3.278502	22	0.000000	0.000000	1.377
28	3.278502	22	0.000000	0.000000	1.377
29	3.278502	22	0.000000	0.000000	1.377
30	3.278502	22	0.000000	0.000000	1.377

29
30

3.2472563	0.0000196	0.0000208	-0.0000007	-3.356
2.9702587	0.0000235	0.0000208	-0.0000027	12.861

ERROR CRITERION

SUM OF SQUARES OF DELTA Y IS 0.2047311E-09

MEAN SQUARE DEVIATION IS 0.6829144E-11

VARIANCE IS 0.4026517E-C9

REGRESSION INDEX OF CORRELATION IS R= 0.98304

TABLE A8-3

FOR FREON - 14 - BENZENE SYSTEM

POLYNOMIAL IS OF DEGREE 1 BASED ON 19 DATA POINTS

THE POLYNOMIAL COEFFICIENTS ARE

A(0) = 0.0000178

A(1) = -0.0000020

POINT	X, EXPERIMENTAL	Y, EXPERIMENTAL	Y, CALCULATED	YEXPT-YCALC	PERCENT ERROR
1	4.1748533	0.0000114	0.0000095	0.0000019	20.199
2	4.2301130	0.0000104	0.0000094	0.0000010	10.673
3	4.1000787	0.0000102	0.0000105	-0.0000003	-17.444
4	3.6151810	0.0000098	0.0000108	-0.0000010	-17.444
5	3.5123968	0.0000117	0.0000113	0.0000004	7.287
6	3.2293095	0.0000121	0.0000119	0.0000002	-5.342
7	2.2254162	0.0000133	0.0000129	0.0000004	2.221
8	2.4229384	0.0000102	0.0000111	-0.0000009	-8.941
9	2.2932512	0.0000099	0.0000117	-0.0000018	-17.905
10	2.9544657	0.0000128	0.0000120	0.0000008	5.220
11	3.3222257	0.0000107	0.0000117	-0.0000010	-9.177
12	3.0895461	0.0000110	0.0000093	0.0000017	10.552
13	3.4235663	0.0000093	0.0000093	0.0000000	0.000
14	3.6774717	0.0000116	0.0000101	0.0000015	12.777
15	3.3611307	0.0000113	0.0000111	0.0000002	1.320
16					
17					
18					
19					

ERROR CRITERION

SUM OF SQUARES OF DELTAY IS 0.3341097E-10

MEAN SQUARE DEVIATION IS 0.1759527E-11

VARIANCE IS 0.1223087E-09

REGRESSION INDEX OF CORRELATION IS R= 0.98561

TABLE A8-4
 POLYNOMIAL IS OF DEGREE 0 BASED ON 135 DATA POINTS FOR NITROGEN-BENZENE SYSTEM
 THE POLYNOMIAL COEFFICIENTS ARE

$A(0) = 0.0000190$

POINT	X, EXPERIMENTAL	Y, EXPERIMENTAL	Y, CALCULATED	YEXPT-YCALC	PERCENT ERROR
1	4.0784807	0.0000154	0.0001190	-0.0000036	-18.8733
2	4.09179157	0.0000193	0.0001190	-0.0000003	-1.8433
3	4.08431744	0.0000243	0.0001190	-0.0000050	-28.5138
4	3.97551072	0.0000160	0.0001190	-0.0000030	-18.5484
5	3.98851685	0.0000256	0.0001190	-0.0000066	-34.6011
6	3.84273248	0.0000209	0.0001190	-0.0000020	-47.7422
7	3.07377691	0.0000158	0.0001190	-0.0000032	-16.9118
8	3.55822692	0.0000179	0.0001190	-0.0000011	-3.5555
9	3.06760992	0.0000184	0.0001190	-0.0000006	-3.3082
10	3.32093224	0.0000189	0.0001190	-0.0000009	-3.5555
11	3.27097224	0.0000240	0.0001190	-0.0000019	-2.9089
12	3.11277659	0.0000297	0.0001190	-0.0000014	-2.3907
13	3.54799328	0.0000237	0.0001190	-0.0000013	-1.7537
14	3.57532028	0.0000183	0.0001190	-0.0000015	-2.9552
15	3.48071217	0.0000187	0.0001190	-0.0000005	-2.1290
16	3.17899061	0.0000147	0.0001190	-0.0000057	-26.5558
17	3.10784473	0.0000283	0.0001190	-0.0000087	-40.5038
18	3.19004573	0.0000133	0.0001190	-0.0000048	-22.5498
19	3.13399026	0.0000143	0.0001190	-0.0000049	-25.6091
20	3.18149261	0.0000161	0.0001190	-0.0000029	-15.5555

ERROR CRITERION
SUM OF SQUARES OF DELTAY IS 0.2369810E-08
MEAN SQUARE DEVIATION IS 0.1755822E-10
VARIANCE IS 0.3780058E-09
REGRESSION INDEX OF CORRELATION IS R= 0.95355

TABLE A8-5
FOR HELIUM - BENZENE SYSTEM

POLYNOMIAL IS OF DEGREE 0 BASED ON 30 DATA POINTS

THE POLYNOMIAL COEFFICIENTS ARE

$$A(0) = 0.0000199$$

POINT	X, EXPERIMENTAL	Y, EXPERIMENTAL	Y, CALCULATED	YEXPT-YCALC	PERCENT ERROR
1	4.1900311	0.0000212	0.0000199	0.0000014	6.907
2	3.7626877	0.0000164	0.0000199	-0.0000034	-17.280
3	4.1426563	0.0000170	0.0000199	-0.0000029	-14.671
4	4.1514235	0.0000184	0.0000199	-0.0000015	-7.492
5	4.0927744	0.0000208	0.0000199	0.0000009	4.644
6	3.7830238	0.0000218	0.0000199	0.0000019	9.614
7	3.7536993	0.0000220	0.0000199	0.0000021	10.702
8	3.4821148	0.0000204	0.0000199	0.0000006	2.836
9	3.6358109	0.0000242	0.0000199	0.0000043	21.630
10	3.7835813	0.0000212	0.0000199	0.0000013	6.664
11	3.1658802	0.0000217	0.0000199	0.0000019	9.312
12	3.2446432	0.0000204	0.0000199	0.0000005	2.672
13	3.0476236	0.0000194	0.0000199	0.0000009	-2.368
14	2.8122158	0.0000208	0.0000199	0.0000009	4.591
15	2.7554827	0.0000171	0.0000199	-0.0000028	-13.954
16	4.1157618	0.0000201	0.0000199	0.0000002	1.134
17	4.2206821	0.0000165	0.0000199	-0.0000034	-16.928
18	3.9650126	0.0000178	0.0000199	-0.0000021	-10.320
19	3.9148369	0.0000166	0.0000199	-0.0000033	-16.704
20	3.5947062	0.0000203	0.0000199	0.0000004	2.197
21	2.7737541	0.0000174	0.0000199	-0.0000025	-12.507
22	3.2761784	0.0000158	0.0000199	-0.0000041	-20.467
23	3.0780525	0.0000203	0.0000199	0.0000004	2.242
24	2.2852564	0.0000283	0.0000199	0.0000084	42.435
25	2.9791002	0.0000178	0.0000199	-0.0000021	-10.453
26	2.8817692	0.0000237	0.0000199	0.0000038	19.021
27	3.6807556	0.0000162	0.0000199	-0.0000036	-18.258
28	3.1823845	0.0000195	0.0000199	-0.0000004	-2.007

-1.304
18.124

-0.0000003
0.0000036

0.0000199
0.0000199

0.0000196
0.0000235

3.2472963
2.9702587

29
30

RRCR CRITERION

SUM OF SQUARES OF DELTAY IS 0.2321942E-09

MEAN SQUARE DEVIATION IS 0.7742428E-11

VARIANCE IS 0.4026517E-09

REGRESSION INDEX OF CORRELATION IS R= 0.98077

TABLE A8-6

POLYNOMIAL IS OF DEGREE 0 BASED ON 19 DATA POINTS FOR FREON - 114 - BENZENE SYSTEM
THE POLYNOMIAL COEFFICIENTS ARE

A(0) = 0.0000109

POINT	X, EXPERIMENTAL	Y, EXPERIMENTAL	Y, CALCULATED	YEXPT-YCALC	PERCENT ERROR
1	1748533	0.0000114	0.0000109	0.0000004	4.1085
2	4.2301130	0.0000104	0.0000109	-0.0000006	-5.1485
3	4.1696301	0.0000103	0.0000109	-0.0000006	-5.1485
4	3.6151810	0.0000098	0.0000109	-0.0000011	-16.4057
5	3.3123968	0.0000116	0.0000109	0.0000007	5.7385
6	3.2293095	0.0000107	0.0000109	-0.0000002	-1.7210
7	2.8354115	0.0000121	0.0000109	0.0000012	9.1075
8	2.4293047	0.0000132	0.0000109	0.0000023	9.3055
9	2.2949757	0.0000153	0.0000109	0.0000044	16.6329
10	2.0532519	0.0000199	0.0000109	0.0000090	17.2249
11	2.0322225	0.0000127	0.0000109	0.0000019	8.7655
12	2.0322225	0.0000107	0.0000109	-0.0000002	-1.7210
13	2.0322225	0.0000110	0.0000109	0.0000001	0.3490
14	2.0322225	0.0000110	0.0000109	0.0000001	0.3490
15	2.0322225	0.0000110	0.0000109	0.0000001	0.3490
16	2.0322225	0.0000110	0.0000109	0.0000001	0.3490
17	2.0322225	0.0000110	0.0000109	0.0000001	0.3490
18	2.0322225	0.0000110	0.0000109	0.0000001	0.3490
19	2.0322225	0.0000113	0.0000109	0.0000004	3.7110

ERROR CRITERION

SUM OF SQUARES OF DELTAY IS 0.5687371E-10

MEAN SQUARE DEVIATION IS 0.2993523E-11

VARIANCE IS 0.1223087E-09

REGRESSION INDEX OF CORRELATION IS R= 0.97552

APPENDIX 9.

COMPUTER PROGRAM FOR THE EVALUATION OF K_G

NOMENCLATURE:

J	ATM	SETS/NUMBER OF EXPERIMENTAL RUNS
N	RHOM	LEVELS IN THE COLUMN
P	RHO	(ATM/CM HG)
R	CMVO	(G/ML)
B	BASE	TRAVEL IN CAPILLARY (CM)
	TEMP	(MILLIVOLTS)
	GRAPH	(DEG. C)
Z	VAPL	(MILLIVOLTS)
V	P	(VOL. IN COLUMN)
P	PRODF	(ATM/CM HG)
D	DIFF	(ATM/CM HG)
S	SATVOL	(ATM/CM HG)
D	DIFF	(ATM/CM HG)
U	R	(ATM/CM HG)
	AREA	(SQ CM)
T	TITLE	(SQ CM)
X	TITLE	(SQ CM)
X	Y	DIFFERENT
Y	W	DIFFERENT
W	VEL	DIFFERENT
VEL	TAREA	DIFFERENT
TAREA	ECC	DIFFERENT
ECC		DIFFERENT

CC

```

INTEGER TITLE(80)
DIMENSION XX(200),YY(200),Z(5),V(5),P(5),PROD(5),PDIFF(5),DIFF(5)
DIMENSION GRATVOL(5),Y(200,3),W(200,3),Q(200,3),NDATA(3)
DIMENSION XXX(200,5),YYY(200,5),ZZZ(200,5),NPNTS(5)
DIMENSION VELA(200,1),TAREA(200,1),ECC(200,1)
DATA AVGVOL,COEFF,DMOL,EQDIA/0.0,0.0,0.0,0.0,0.0,0.0,0.0/

```

```

READ(1,1)J,N

```

```

NDATA(1)=J
NDATA(2)=J
NDATA(3)=J

```

```

NFX NS=1 MC=1 JLE(1),I=1,80

```

```

DREAD(1,2)(TIM,PHOM,CMVO,BASE,TEMP

```

```

READ(1,4)(GRAPH(I),Z(I),I=1,N)
DATA VAPL,RHOB,RHOC/0.0,0.0,0.0/

```

```

INITIAL VOLUME OF RUBBLE

```

```

VIN=CMVO*0.07368

```

```

CALCULATION OF DENSITY AND VAPOR PRESSURE OF BENZENE
FROM TEMPERATURE DEPENDENT EQUATIONS

```

```

CALL DENS(RHOB,TEMP)
CALL VAPOR(VAPL,TEMP)

```

```

WRITE(3,22) MC TITLE(1),I=1,80)
WRITE(3,31)(TIM
WRITE(3,80)PAMP
WRITE(3,81)TEMP
WRITE(3,82)RHOB
WRITE(3,83)VAPL
WRITE(3,84)RHOC
WRITE(3,85)VIN

```

C C

CCC CCCC C

CCCCC

CALCULATION OF BUBBLE VOLUME AND ASSOCIATED PRESSURE
AT REFERENCE LEVEL IN COLUMN

```

DO 400 I=1,N,GRAPH(I))*23.2*C.07368+VIN
V(I)=(PAIN+RHOB*Z(I)/RHOM)/76.0
IF(I.EQ.1) GO TO 500
GO TO 501
500 VJ=V(I)
PO=V(I)
PDIFF(I)=P(I)-VAPL
POVO=P(I)*V(I)
SATVOL(I)=POVO/PDIFF(I)
WRITE(3,3)V(I),SATVOL(I),DIFF(I),P(I),POVO,Z(I),GRAPH(I)
GO TO 401
501 CONTINUE
PDIFF(I)=P(I)-VAPL
POVO=P(I)*V(I)
SATVOL(I)=POVO/PDIFF(I)
DIFF(I)=SATVOL(I)-V(I)
WRITE(3,3)V(I),SATVOL(I),DIFF(I),P(I),PROD(I),Z(I),GRAPH(I)
GO TO 401
401 I=1,MC,I)=V(I)
IXX(MC,I)=SATVOL(I)
YZZ(MC,I)=DIFF(I)
NBN(I)=J
CONTINUE
400 WRITE(3,87)
WRITE(3,86)

```

CCCCCCCC

EVALUATION OF AVERAGE MASS-TRANSFER COEFFICIENTS

FIRST SECTION-CLOSEST TO THE INTERFACE

I=1

```

M=I+1
PR1=P(I)
PR2=P(M)
VOL1=V(I)
VOL2=V(M)
VO=VOL1
PO=PR1
COEFFS(PRI,PR2,VOL1,VOL2,VO,PO,RHOB,VAPL,TEMP,I,M,AVGVOL,
EQDIA,U,AREA,E)
COEFF(I)=COEFF
AVGVOL(I)=AVGVOL
AMODIA(I)=AMODIA
EQDIA(I)=EQDIA
VAPL(I)=VAPL
RHO(I)=RHO
TARBEAC(MC,I)=AREA
TCC(MC,I)=TCC
XX(MC,I)=XX(MC,I)
YY(MC,I)=YY(MC,I)
DD(9000,I)=1
XTITLE(MC,I)=TITLE(I)

```

9000
CCC

SECOND SECTION

```

I=2
M=I+1
PR1=P(I)
PR2=P(M)
VOL1=V(I)
VOL2=V(M)
VO=V(K)
PO=PR1
COEFFS(PRI,PR2,VOL1,VOL2,VO,PO,RHOB,VAPL,TEMP,I,N,AVGVOL,
EQDIA,U,AREA,E)
COEFF(I)=COEFF
AVGVOL(I)=AVGVOL
AMODIA(I)=AMODIA
EQDIA(I)=EQDIA
VAPL(I)=VAPL
RHO(I)=RHO
TARBEAC(MC,I)=AREA
TCC(MC,I)=TCC
XX(MC,I)=XX(MC,I)
YY(MC,I)=YY(MC,I)
DD(9000,I)=1
XTITLE(MC,I)=TITLE(I)

```

CCC

THIRD SECTION

I=3

```

M=I+1
K=I-2
PR1=P(I)
PR2=P(M)
VOL1=V(I)
VOL2=V(M)
VD=V(K)
PO=P(K)
POE=V(K)
CALL VAEP(VAPL,TEMP)
CALL COEFFS(PRI,PR2,VOL1,VOL2,VO,PO,RHOB,VAPL,TEMP,I,M,AVGVOL,
C COEFF,DMOLES,EODIA,U,AREA,E)
1C COEFF,DMOLES,EODIA,U,AREA,E)
X(MC,3)=AVGVOL
Y(MC,3)=DMOLES
W(MC,3)=EODIA
Q(MC,3)=AREA
Q(NTINUE)
200

```

0000000

DATA PLOTTING

IN CASE OF NEGATIVE VALUE
SET VALUE=0.1E-08

```

DO 7000 I=1,J
DO 7000 M=1,3
IF(X(I,M))7500,7500,7700
X(I,M)=0.1E-06
IF(W(I,M))7800,7800,7900
W(I,M)=0.1E-06
CONTINUE(2)
WRITE(3,6003)
WRITE(3,6002)
WRITE(3,6000) X(MC,1),X(MC,2),X(MC,3),W(MC,1),W(MC,2),W(MC,3),MC=1

```

7500
7700
7800
7900

```

1 WRITE(3,32)
WRITE(3,3204)
WRITE(3,6002)
WRITE(3,6000) Y(MC,1),Y(MC,2),Y(MC,3),Q(MC,1),Q(MC,2),Q(MC,3),MC=1
1 YMIN=5.5
YMAX=0.00003

```

WMIN=0.000001
QMAX=2.15
QMIN=1.50
WRITE(3,50)

CCCCC

SEMI-LOG PLOT SUBROUTINE

CALL PLOTS(X,Y,NDATA,NFXNS,YMAX,YMIN)
WRITE(3,50)
CALL PLOTS(X,O,NDATA,NFXNS,QMAX,QMIN)
WRITE(3,50)
CALL PLOTS(X,W,NDATA,NFXNS,WMAX,WMIN)
WRITE(3,50)
CALL PLOTS(M,Y,NDATA,NFXNS,YMAX,YMIN)
WRITE(3,50)
WRITE(3,51)
WRITE(3,53)

CCCCC

LINEAR PLOT SUBROUTINE

CALL MPLOTS(XXX,YYY,NPNTS,N,2,81,57,80,56)
WRITE(3,33)
CALL MPLOTS(XXX,ZZZ,NPNTS,N,2,81,57,80,56)
WRITE(3,32)
DO 999 I=1,5
WRITE(3,700)
KK=I-1

CCCCC

CURVE FITTING SUBROUTINE

9999 CALL CURVE(YY,XX,KK,J)
DO 9000 MC=1,J

SUBROUTINE FOR THE CALCULATION OF THE DENSITY OF BENZENE FROM
A TEMPERATURE DEPENDENT EQUATION

SUBROUTINE DENS(RHOB,TEMP)

RHOB=1.18681-0.00105*TEMP
RETURN
END

000000 00

SUBROUTINE FOR THE CALCULATION OF THE VAPOR PRESSURE
FROM A TEMPERATURE DEPENDENT EQUATION

SUBROUTINE VAPOR(VAPL,TEMP)

A=18.3801
B=4122.139
VAPL=(EXP(A+B/TEMP))/760.0
RETURN
END

CCCCC CC

