A General Study of Diffusion Pumps--Langmuir Type

Thesis

by

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C O N T E N T S

Some Simple Vacuum Technique

Introduction

Gaede invented the diffusion pump and published his theory of the diffusion of gas through mercury vapor in 1915.[1] Langmuir in 1916 independently constructed a new type of diffusion pump.[2] The Langmuir type of diffusion pump, because of its high speed and simple construction, has become an important item in modern science research laboratories.

1. General Mechanism: Fig. 1 shows a longitudinal section of the main part of the Langmuir type of diffusion pump. Vapor of heavy molecular weight from a boiler (not shown in the figure) passes through tube T, expands at jet P, and after being condensed on the cooling wall S_1S_2 returns back as liquid to the boiler through M. S uch a distilling process produces a pressure difference of contained gas at R and M. Accordingly, if the original gas pressure is low, a high vacuum will be produced in R.

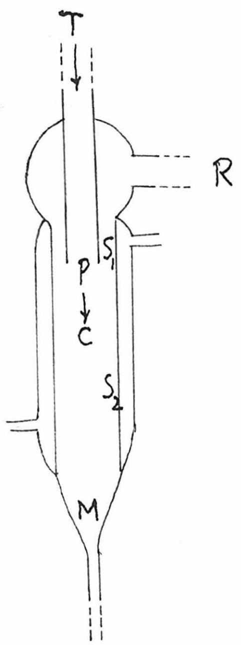

Fig 1

2. The principle of production of a high vacuum: Suppose that the system is originally in low vacuum. The vapor escapes at P in all directions and with velocity which is the same as molecular velocity of thermal agitation at T. The mean vapor molecular velocity is given by

$$\overline{V}_m = \sqrt{\frac{8p}{\pi\rho}} = \sqrt{\frac{8RT}{\pi m}},$$

where p, ρ, T, M are respectively pressure, density, temperature, molecular weight of the vapor, and R equals gas constant.

The mean momentum of each vapor molecule is then

$$\bar{V}_m \frac{M}{N} = \frac{1}{N}\sqrt{\frac{8RMT}{\pi}} ,$$

where N is Avogadro's number. This shows that the momentum of escaping vapor is directly proportional to the square root of the molecular weight and temperature of the vapor. Although the vapor molecules escape at the jet in all directions, the intensity of the vapor stream is different in different directions, because the effective area from which the vapor starts to escape in different directions is different; generally, the intensity of the stream is greatest directly under the jet, gradually becoming smaller on getting away from the downward direction and becoming very small in the upward direction. That is, there is a greater total momentum of vapor in the downward direction, and consequently more gas molecules are driven downward by vapor. It is possible by adjusting the temperature of the boiler to make the downward vapor stream so dense that very few of the total gas molecules caught by it can get back and the intensity of the upward vapor stream is still so weak that it can not prevent the gas molecules from diffusing downward through it. In other words, the gas molecules diffuse downward through the upward vapor stream and are washed away by the downward vapor stream. A high vacuum in R. therefore results.

3. Theoretical consideration of the factors concerning the speed of the diffusion pump: We define the opening between the tip of the nozzle and the cooling wall as the slit. In the space above the slit the vapor, according to its different states of motion, is to be considered as of two types; namely, directional vapor and non-directional vapor. The directional vapor is directly radiated in from the slit and has its upward component of momentum, while the non-directional vapor is produced by re-evaporation and collision, and possesses thermal agitation which depends on the temperature of the wall.

We first consider that the gas molecules diffuse through the directional vapor alone. Gaede analytically treated this kind of diffusion process. He reached the conclusion that the number of gas molecules striking per unit time on the slit of area q is

$$z = \frac{1}{4} \alpha q N \Omega, \qquad (1)$$

where $N =$ concentration of gas molecules ,

$\Omega =$ mean velocity of gas molecules ,

$\alpha = f\left(\frac{\lambda}{d}\right)$, where $\lambda =$ mean free path of gas molecules in vapor, and $d =$ width of the slit.

But, N cannot be the same throughout the space containing vapor, especially due to the presence of the non-directional vapor. So, we should also consider the diffusion of the gas molecules through the non-directional vapor. There is an analogy as noticed by Gaede, at low pressure, between the diffusion of the gas through capillary tube and that through the vapor. Thus, from Knudsen's expression (3) for the rate of flow of the gas at low pressure through a tube of length ℓ and diameter D,

$$U = A \frac{D^3}{l} , \qquad (2)$$

where A is a constant which depends on the molecular weight and the temperatureof the gas only, we can easily deduce the following expression for the gas pressure (partial) gradient along the path of diffusion through vapor ,

$$\frac{dp}{dx} = -p_0 k , \qquad (3)$$

where p_0 is the partial pressure of the gas at a section of reference in the path, and k is a constant which depends only on the porousity of the vapor and does not involve A in (2).

Since N is proportional to p, we have, from (3),

$$\frac{dN}{dx} = N_0 k , \qquad (4)$$

where N is the gas molecular concentration corresponding to p_0.

Integrating (4), we get the gas molecular concentration near slit,

$$N = N_0 (1 - kS) , \qquad (5)$$

where S = whole path from N_0 to N.

Putting $\beta = 1 - kS$, and substituting in (1), we have

$$z = \frac{1}{4} \alpha \beta q N_0 \Omega . \qquad (6)$$

If there were no chance for gas molecules which enter the slit to return, there would be z gas molecules per unit time carried away by the vapor stream C. Actually there are some gas molecules which rebound from some vapor molecules whose downward component of velocity is small.

Let n_1 = number of gas molecules which rebound from vapor C per unit time, and assume this is directly proportional to z; i.e., $n_1 = k_1 z$.

Let n_2 = number of gas molecules diffusing back per unit time because of the pressure in the fore vacuum and assume that this depends on the fore pressure only.

Then the total number of gas molecules extracted per unit time is

$$Z = z - n_1 - n_2$$
$$= \frac{1}{4}\alpha\beta\gamma N_0 q \Omega - n_2, \qquad (7)$$

where $\gamma = 1 - k_1$, which is equivalent to Gaede's "extracting power" of the vapor.

If the fore pressure is low in comparison with the vapor pressure, n_2 is practically zero, then

$$Z = \frac{1}{4}\alpha\beta\gamma N_0 q \Omega. \qquad (8)$$

To express the speed of the pump, substituting $N_0 = \frac{\rho}{m}$ and $\Omega = \sqrt{\frac{8p}{\pi\rho}}$, where ρ, p, m are density, pressure, mass per molecule, of the gas respectively, in (8), and using the perfect gas law, we obtain the volume of the gas extracted per unit time

$$V = \alpha\beta\gamma q \sqrt{\frac{RT}{2\pi M}}. \qquad (9)$$

This is called the speed of the pump.

Equation (9) shows that the ideal maximum speed of a pump cannot exceed the speed of escape of a gas into a perfect vacuum. For, the ideal maximum values of α, β and γ are all unity (i.e., in case there is no vapor dispersed through the slit and no gas molecules rebound from the vapor stream C). When they are unity, the speed is

$$V = q\sqrt{\frac{RT}{2\pi M}} ,$$

which is the speed of a gas escaping into a vacuum through an opening of area q , obtained by considering the well-known expression for number of gas molecules striking per unit time on area q ,

$$z = \frac{1}{4} N \Omega q .$$

Discussion of the Experimental Facts

1. Effect of fore pressure on speed:

Table 1.

Pump I, Mercury, working at 10 mmHg.

Wattage = 229 watts
Vapor Pressure = 4.4 mm Hg.
Cooling Tempeature = 24°C
Tube Resistance 1/8130

Fore Press. in mmHg.	Apparent Speed in cc (air)
2.9×10^{-3}	860
3.2×10^{-3}	860
9.0×10^{-3}	885
.35	890
1.07	860
1.16	840
1.18	785
1.20	390
1.22	5

Before verifying the speed expression (9) we should first justify the assumption that the number of gas molecules diffusing back per unit time, n_2 in equation (7), is negligible at low fore pressure. As Langmuir's own investigation (4) shows, "In nearly all the cases the speed of a pump is practically independent of the exhaust (fore) pressure against which it operates unless this is raised to a certain rather critical value at which the pump ceases operating satisfactorily" the same result is shown in Table 1.

This shows that, under the specified conditions, this pump works equally well at all the fore pressures below 1.18 mmHg. The rapid decreasing of the speed at a fore pressure above 1.18 mmHg will be discussed in 4.

2. Effect of fore pressure on high vacuum:

The Table 1 alone is not sufficient to show that the

Table 2.

Pump I, Mercury.

Wattage = 229 watts
Vapor Pressure = 4.4 mmHg
Cooling Temperature = 24°C

Fore Press. in mm	High Vacuum in mm
0.30	below 10^{-5}
0.56	" "
0.81	" "
1.04	" "
1.18	0.11×10^{-4}
1.20	0.19 x "
1.22	0.67 x "
1.23	1.40×10^{-2}
1.25	3.40 x "
1.30	9.10 x "

decreasing of the speed at high fore pressure is due to the large magnitude of n_2 in equation (7). To supply this information, the relation between fore pressure and vacuum must be investigated. The result is shown ih Table 2.

There is a similarity between Table 1 and Table 2, especially the sudden change in vacuum as well as speed at fore pressure about 1.22 mmHg.

3. Effect of vapor pressure in boiler on high vacuum:

Dushman experimentally showed the dependence of the vacuum on the vapor velocity (5). This is also an alternative proof that n_2 in equation (7) depends on the magnitude of the fore pressure in comparison with the vapor pressure. So, the important condition specified here is the constant fore pressure. Table 3 shows an example.

Table 3.

Pump I, Mercury.

Fore Press. = 0.30 mm Hg
Cooling Temperature = 24°C

Watts	Vapor Press. in mm	High Vacuum in mm
333	11.0	below 10^{-5}
261	6.0	" "
171	3.5	" "
151	2.0	" "
133	1.7	" "
114	1.4	0.124×10^{-4}
96	1.3	0.73 x "
87	1.2	1.36 x "
76	1.1	6.3 x "
67	1.0	66.0 x "
60	0.9	320.0

4. Critical fore pressure:

From the above experiments it is noticed that at certain fore pressures, when keeping vapor pressure constant, or at certain vapor pressure, when keeping fore pressure constant, both speed and vacuum are unstable, and if we change by a few per cent this fore pressure or vapor pressure, the corresponding speed and vacuum will change their magnitudes ten or a hundred-fold. Call this fore pressure "critical fore pressure". The critical fore pressure has practical importance. It increases with the vapor pressure in the boiler and is nearly directly proportional to the difference of pressure between the nozzle and fore side. Table 4 shows the proportionality. For a divergent nozzle such as that of Pump II, the critical fore pressure is not so sharp.

Table 4.

Pump I, Mercury.

Cooling Temperature = 23°C

Watts	Vapor Press. in mm	Critical Fore Pressure in mm	
76	1.1	0.30	$\frac{1.1-.3}{.3} = 2.66$
229	4.4	1.20	$\frac{4.4-1.2}{1.2} = 2.67$
261	6.0	1.72	$\frac{6.0-1.72}{1.72} = 2.49$
333	11.0	2.80	$\frac{11-28}{28} = 2.93$

5. Effect of molecular weight of gas pumped on speed:

Consider that the partial pressure of the gas in the vapor is so low that there would be no collision between gas molecules themselves and that the vapor above the slit is not so dense that the mean free path of the gas molecules in the vapor would differ little for different sizes of ordinary gas molecules. So, the factor α as well as β in equation (9) would be the same for different gases. Then, by equation (9), the speed of the pump is inversely proportional to the square root of the molecular weight of the gas. From Tables 5-7, which show the speeds of the pump for H_2, air, CO_2 respectively,

Table 5.

Pump II, Mercury.

Watts = 229
Vapor Press. = 4.5 mm Hg
Cooling Temperature = 24°C
Tube Resistance = $1/(8130 \times \sqrt{M_{air}/M_{H_2}})$

p' Flowmeter Pressure in mm	p Pump Pressure in mm	Apparent Speed for H_2 in cc	$\frac{p \times 10^{-5}}{p'}$
19.0	9.55×10^{-4}	5220	
12.5	5.46 x "	4850	
9.2	3.54 x "	4800	
6.0	2.08 x "	4350	
4.25	1.31 x "	4400	3.08
3.09	.84 x "	4370	2.72
2.09	.533 x "	4100	2.55
1.41	.345 x "	4140	2.41
.766	.190 x "	4300	2.48
.377	.091 x "	4180	2.41
		mean, 4470	

Table 6.

Pump II, Mercury.

Watts = 229
Vapor Press. = 4.5 mm Hg
Cooling Temperature = 24°C
Tube Resistance 1/8130

p' Flowmeter Pressure in mm	p Pump Pressure in mm	Apparent Speed for air in cc	$\frac{p \times 10^{-5}}{p'}$
16.4	12.2×10^{-4}	1390	
14.1	9.4 x "	1380	
11.6	6.7 x "	1360	
9.4	4.7 x "	1340	
6.0	2.37 x "	1350	
4.4	1.61 x "	1240	3.65
2.82	.76 x "	1360	2.68
2.12	.54 x "	1300	2.65
1.10	.275 x "	1270	2.47
.82	.208 x "	1200	2.53
		mean, 1320	

Table 7.

Pump II, Mercury.

Watts = 229
Vapor Press. = 4.5 mmHg
Cooling Temperature = 23°.5C
Tube Resistance = $1/(8130 \times \sqrt{M_{air}/M_{CO_2}})$

p' Flowmeter Pressure in mm	p Pump Pressure in mm	Apparent Speed for CO_2 in cc	$\frac{p \times 10^{-5}}{p'}$
12.8	8.32×10^{-4}	1260	
9.9	5.45 x "	1250	
6.8	3.01 x "	1200	
3.53	1.30 x "	1100	3.68
1.76	.470 x "	1180	2.67
1.23	.313 x "	1080	2.54
.79	.197	1190	2.49
		mean, 1180	

we have to compare the ratios

$$\frac{V_{H_2}}{V_{air}} = 3.40 \quad \text{and} \quad \frac{V_{air}}{V_{CO_2}} = 1.12$$

with $$\frac{\sqrt{M_{air}}}{\sqrt{M_{H_2}}} = 3.81 \quad \text{and} \quad \frac{\sqrt{M_{CO_2}}}{\sqrt{M_{air}}} = 1.22,$$

And from Gaede and Keesom's data (6), V_{He} = 422 liters and V_{air} = 130 liters, the corresponding ratios are

$$\frac{V_{He}}{V_{air}} = 3.22 \qquad \frac{\sqrt{M_{air}}}{\sqrt{M_{He}}} = 2.70.$$

These show that the speed is nearly inversely proportional to the square root of the molecular weight.

Gaede had an explanation for his different experimental results.(7)

6. Indirect verification of Knudsen's Law of molecular flow:

Knudsen's law of molecular flow through a tube is expressed by equation (2), or by writing out the value of A, we have

$$U = \frac{\sqrt{2\pi}}{6}\,\frac{D^3}{\ell}\sqrt{\frac{RT}{M}}\,, \qquad (2')$$

and the speed of the pump is given by

$$V = \alpha\beta\gamma\sqrt{\frac{RT}{2\pi M}}\,. \qquad (9')$$

By the present method of measuring the speed of the pump (see Appendix I), we have, if the flow as shown in

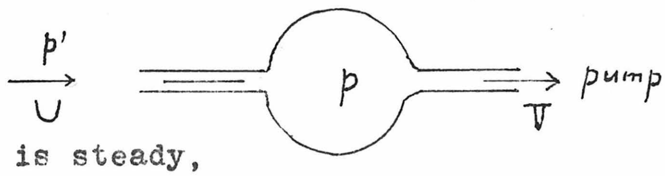

Fig 2

Fig. 2 is steady,

$$pV = \frac{p'+p}{2}\,U$$

or $$\frac{p}{p'+p} = \frac{U}{2V} = \frac{1}{12\alpha\beta\gamma}\,\frac{D^3}{\ell}\,,$$ by (2') and (9').

But p is negligibly small in comparison with p'.

$$\therefore \quad \frac{p}{p'} = \frac{1}{12\alpha\beta\gamma}\,\frac{D^3}{\ell}\,.$$

This shows that (1) $\frac{p}{p'}$, at low p' (since equation (2') is true only for low pressure) is a constant; and, (2) $\frac{p}{p'}$ at low p' is independent of the gas used.

The last columns of Tables 5, 6, and 7 verify that, as p' decreases, not only does the ratio p/p' approach a constant for each gas, but also that this constant is the same for different gases.

7. Effect of vapor pressure on speed:

The factors α and γ in equation (9) depend on the vapor pressure. α decreases as the vapor pressure increases, because the increasing of vapor pressure intensifies the dispersion of vapor through the slit; γ probably increases as vapor pressure increases because the high velocity of the vapor stream would prevent the gas molecules from rebounding; and n_2 in equation (7) is large at low vapor pressure as shown in 3. Hence, there is a maximum speed at a certain vapor pressure. Tables 8 to 11 show respectively the four different speeds corresponding to four different vapor pressures. The maximum speed is at vapor pressure somewhere around 4.4 mmHg. Table 13 shows the different speeds at different vapor pressures and the maximum speed at 5.0 mm butyl phthalate. From these and Molthan's result[(8)] on measuring the pump speeds at different mercury vapor velocities and different rates of condensation of mercury, we can conclude; the speed decreases as vapor pressure increases except at low vapor pressures, at which it has a maximum.

Table 8.

Pump I, Mercury

Watts = 171
Vapor Press. = 3.5 mm Hg.
Cooling Temp. = 23°C
Tube Resistance = 1/8130

p in 10^{-4} mm	Apparent Speed for Air in cc
23.0	916
9.1	905
6.85	847
3.72	843
1.96	830
1.19	848
.44	850
.18	820

Table 9.

Pump I, Mercury

Watts = 229
Vapor Press. = 4.4 mm Hg
Cooling Temp. = 23°.5 C
Tube Resistance = 1/8130

p in 10^{-4} mm	Apparent Speed for Air in cc
17.6	878
9.2	858
4.83	890
2.92	913
1.88	930
1.02	915
.67	890
.46	890
.30	920

Table 10.

Pump I, Mercury

Watts = 261
Vapor Press. = 6.0 mm Hg
Cooling Temp. = 23°.5 C
Tube Resistance = 1/8130

p in 10^{-4} mm	Apparent Speed for Air in cc
13.1	830
6.43	855
5.42	795
4.03	807
2.63	800
1.15	820
.50	825
.40	790
.30	800

Table 11.

Pump I, Mercury

Watts = 333
Vapor Press. = 11.0 mm Hg
Cooling Temp. = 22°.5 C
Tube Resistance = 1/8130

p in 10^{-4} mm	Apparent Speed for Air in cc
22.9	791
9.4	819
3.94	786
3.09	778
1.56	786
.62	740
.37	760
.23	780

8. Independence of speed and gas pressure:

According to equation (9), the speed is independent of the partial pressure of the gas to be extracted. Gaede experimentally verified it by his first diffusion pump. Tables 5 to 11 show the independence of the speed and the pressure at which the pump works.

9. Temperature of cooling system and speed:

The presence of non-directional vapor both above and below the slit lowers the efficiency of the pump. This vapor is largely produced by re-evaporation on the wall S_1 S_2 (Fig. 1) which in turn depends on the temperature on the wall. So, the factor β in equation (9) can be greatly increased by lowering the temperature of S_1; this is the reason why in Gaede and Keesom's high speed pump a special cooling system round the outer wall of the nozzle is necessary (9). By lowering the temperature of S_2 the factor γ in equation (9) is also increased. Table 12 shows the importance of the low temperature of the cooling system. It is interesting to note that if the pump specified in Table 12 operates in open air, the cooling system running by water of open air temperature, the speed in winter will be twice as large as that in summer.

Table 12.	Cooling Temp. In degrees C.	Apparent Speed for Air in cc.
Pump I, Mercury working at 10^{-4} mmHg	41.9	540
	37.2	610
Vapor Press. = 6.0 mmHg	32.0	680
Tube Resis. = 1/8130	29.0	728
	26.0	755
	23.0	807
	18.3	853
	11.9	1010
	3.0	1050
	-1.0	1060
	-4.0	1060

10. Comparison of efficiencies of mercury vapor and n-butyl phthalate vapor pumps:

As recommended by Hickman and Sanford[10], n-butyl phthalate is among one of the most efficient substitutes for mercury. Besides retaining all the characteristics of the mercury vapor pump, the n-butyl phthalate vapor pump is proved to have much

Table 13.

Pump I, n-butyl Phthalate

Fore Pressure = .09 mm Hg
Cooling Temp. = 25°C

Watts	Vapor Press. in mm butyl phthalate	Speed for Air in cc.
80	2.0	2180
110	3.5	2420
142	5.0	2500
175	8.0	2040
210	11.0	1840
250	14.0	1640
300	18.0	1260

higher speed, as shown in Table 13, which is nearly twice as large as that of mercury vapor pumps. The only objection is the slow production of volatile matter, especially when operating with high fore pressure of air. The gas thus produced seems to be incompletely trapped even at liquid air temperature.

11. Shape of nozzle and speed:

The shape of the nozzle directly affects the characteristics of the jet of the vapor stream and hence the factor in equation (9). The divergent nozzle with narrow throat, first introduced by Grawford[11] in his pump, then adopted in other designs of pump as Gaede and Keesom's high speed pump, and recently investigated by Hickman and Sanford[12], is proved to be the most efficient. By this form of nozzle, the vapor expands at throat A (fig. 4) instead of expanding at the mouth as in the case of a straight nozzle. Accordingly, we get greater downward momentum of the vapor before leaving the nozzle; thus, on leaving the nozzle, the relative amount of the vapor dispersed through the slit is reduced so as to increase the factor α. Tables 6 and 9 show respectively the speeds with divergent nozzle and with straight nozzle.

12. Speeds of diffusion pumps of different size and form used in this laboratory:

Results are shown in the following tables.

Table 15.

Pump IV, Mercury

Watts = 2000 watts
Fore Press. = .002 mmHg
Cooling Temp. In. = 23°C
" " Out. = 28°C
Tube Resistance = 1/8130
Trap Temp. (liquid air)

p in 10^{-4} mmHg	Speed for Air in cc Apparent	True
5.25	5570	
4.55	5400	
2.58	5310	
1.07	5500	
.98	5610	
.67	5200	
.45	5500	
mean,	5400	10900

Table 14.

Pump IV, Mercury

Watts = 1500
Fore Press. = .002 mmHg
Cooling Temp. In. = 23°C
" " Out. = 32°C
Tube Resistance = 1/8130
Trap Temp. = 0°C

p in 10^{-4} mmHg	Speed for Air in cc Apparent	True
5.95	4200	
4.34	3920	
2.51	4150	
1.79	4110	
1.09	4080	
.80	4270	
.40	4150	
.32	3910	
mean,	4100	6610

Table 16.

Pump III, Mercury

Vapor Press. = 7.5 mm
Fore Press. = 0.1 mm
Watts = 145
Cooling Temp. = 23°C
Tube Resis. = 1/9810

p in 10^{-4} mmHg	Speed (air) Apparent in cc
45.0	534
28.3	530
19.6	502
11.1	493
8.08	450
6.85	431
2.60	392
1.47	313

Table 17.

Pump V, Mercury

Vapor Press. = 1.45 cm
Fore Press. = 0.1 mm.
Watts = 270
Cooling Temp. = 22°C
Tube Resis. = 1/2720

p in 10^{-4} mmHg	Speed (air) Apparent in cc
20.3	644
6.6	630
4.0	653
2.91	672
.83	646
.72	628
.44	595
.22	600
.21	570

The decreasing of speed with pressure of Pump III shown in Table 16 is due to the "leaking Back" from fore vacuum because of the small nozzle and high fore pressure. The constant quantity of "leaking back" can be easily estimated from the table.

DIAGRAMS OF PUMPS

Punp I

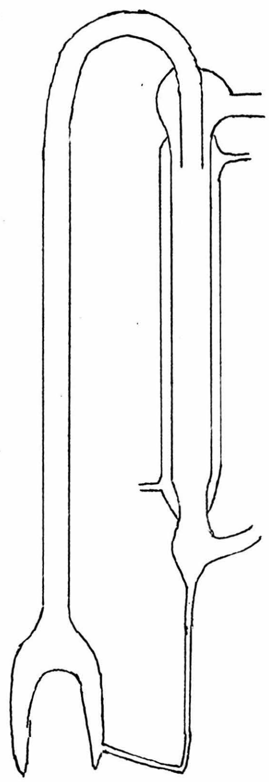

Fig 3

Pump II

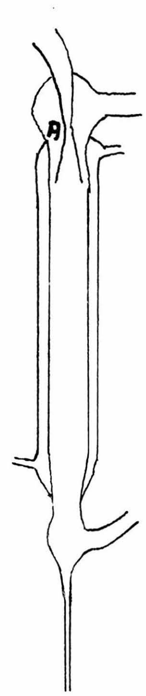

Fig 4

Pump V

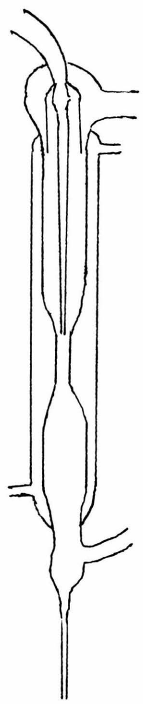

Fig 5

Pump III

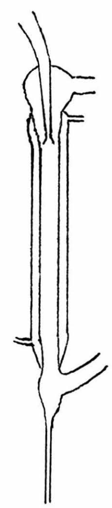

Fig 6

scale rtio, $\frac{1}{5}$

Pump IV

scale ratio, $\frac{1}{5}$

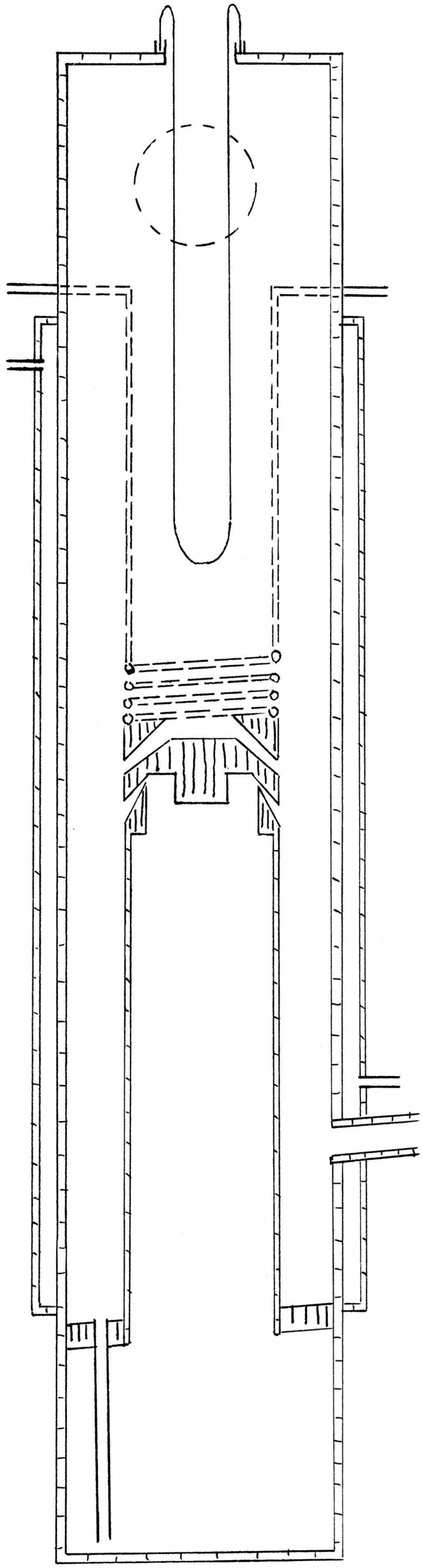

Fig 7

APPENDIX I

A Low Pressure Gas Flowmeter

1. For measuring the speed of a vacuum pump.

(a) Absolute method: The flowmeter is schematically shown in Fig. 8. Any vacuum pump whose speed is to be measured is connected to A'. Through C the gas is allowed to leak into the vacuum system. The gas pressure on the right side of C is first regulated by E and then kept constant by I (or by a pressure-increaser connected at K) when it is observed that there is no change of galvanometer deflection of gauge B.

Let V = volume of the gas leaking in during a time interval t. This is measured by the known volume of mercury raised in F.

Let P' = pressure of the gas on the right side of C. This is measured by G when it is low, or by the difference of the mercury surfaces in F and H when it is high.

Let P = pressure of the gas in the vacuum system at which pressure the speed of the pump is determined. This is measured by B.

Then the apparent speed of the pump at pressure P is

$$S = \frac{P'V}{tP} .$$

(b) Calibration method: To avoid the tedious work of keeping the pressure constant and of recording the rate of flow we calibrate the capillary leak for each gas.

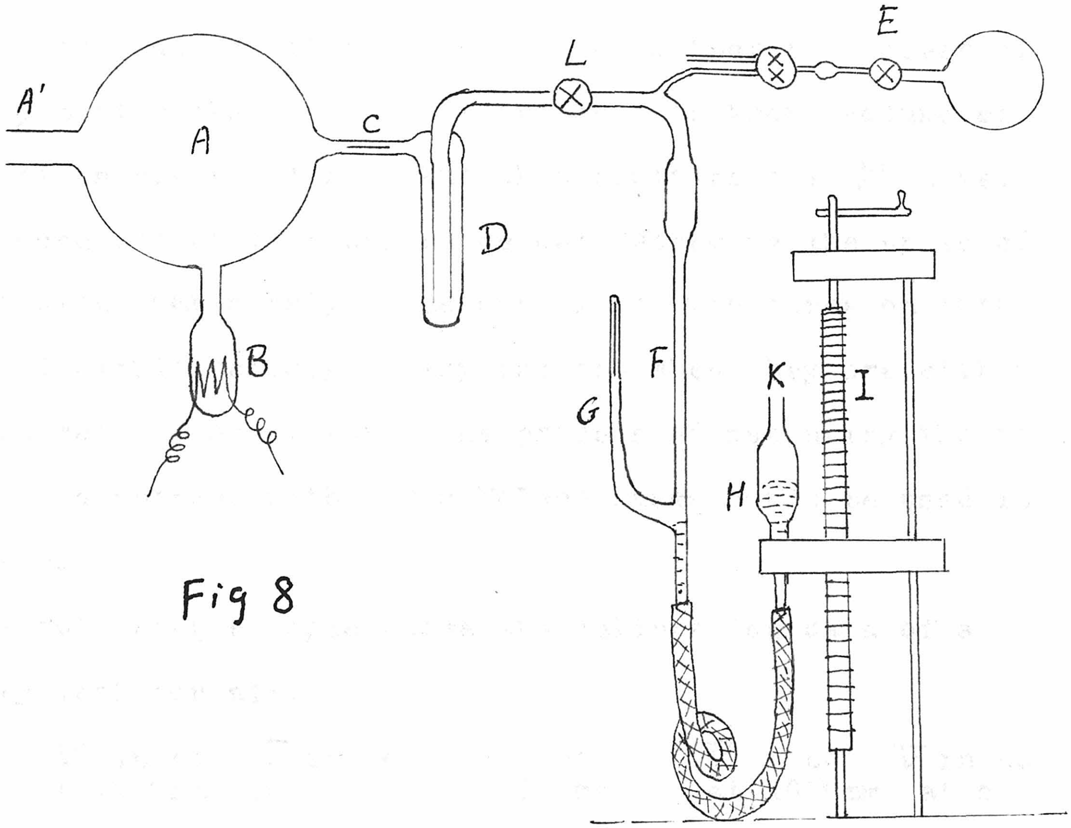

Fig 8

A glass bulb of volume about 8000 cc.

A' glass tube about 3 cm. in diameter.

B hot wire gauge (or ionization gauge).

C capillary leak.

D mercury trap.

E reducer.

F tube of known dimension.

G small McLeod gauge.

H mercury reservoir.

I screw device for slow up-and-down motion of H.

L stop cock.

To each pressure p' at F, when A is in high vacuum, the corresponding rate of flow is determined either by process of (a) or by noting the increase of pressure in known volume of A (when it is closed at A'), and then plotting a $V-p'$ curve.

By such calibration curves we can determine the speed of any diffusion pump merely by measuring the pressures on both sides of C simultaneously at any instant when they are either slowly decreasing or steady. The process of measuring the rate of flow is dispensed with and a McLeod gauge could be used in place of B.

The following example shows the calibration data of a capillary leak for air.

p' in mm	V in cc at 10^{-4} mm	V in cc at p'	p' in mm	V in cc at 10^{-4} mm	V in cc at p'
20.2	24600	.122	2.66	928	.0349
17.2	18400	.107	2.19	705	.0323
14.5	13900	.096	1.79	573	.0320
13.1	11400	.087	1.40	440	.0315
11.4	8720	.0765	0.91	290	.0319
9.5	6380	.0672	0.62	195	.0314
5.88	3400	.0577	0.531	167	.0325
4.80	2260	.0470	0.342	106	.0310
4.10	1790	.0437	0.257	77.5	.0300
3.35	1300	.0388			

The above data is sufficient to show that at high p', V_p is directly proportional to p' (Poisenille's law on the flow of fluid through a capillary tube), and at low p', is independent of p' (Knudsen's law of molecular flow).

2. For maintaining automatically a constant high vacuum -- another method of measuring the speed of vacuum pump.

The constant pressure in A (Fig. 8) is kept by gas in F, in which the pressure in turn is regulated by an electric mercury valve automatically.

Since a hot wire gauge B (or an ionization gauge) is used to measure pressure in A, this pressure is indicated by the deflection of the galvanometer, so the galvanometer, owing to its deflection, can be used as a contact key. Name it "galvanometer contact". By the action of the "galvanometer contact" and a system of relays, it is easy to operate the electric mercury valve.

To form a "galvanometer contact", as shown in Fig. 9, g being the galvanometer coil and mirror (the author used a Leeds and Northrup Co. Type P galvanometer), use two pieces of fine platinum wire Pt, one attached horizontally to the lower side of the galvanometer coil, the other fixed vertically on the side of the lower suspension, both should be carefully insulated from the galvanometer circuit, and their relative positions should be such that at certain required deflection positions of the mirror (i.e., at certain required pressure in A) they make contact with each other.

But a very small current in the "galvanometer contact" will cause two wires to stick together. This kind of difficulty usually occurs in small current relays as pointed out and eliminated by Roberts[13]. To eliminate this, let the "galvanometer contact" control a vacuum tube amplifier. When the two platinum wires are in contact, they produce a sufficient negative voltage on the grid to reduce the plate current nearly to zero, and this to operate the relay in plate circuit. For amplifier, tube 201A, plate voltage 120 volts, $L_1 = 10,000$ ohms, $L_2 = 10$ megohms, grid voltage $= -20$ volts are used. The following care should be taken: Do not put too many volts in the plate circuit, because a high plate voltage will produce an ionization current in the grid circuit, and hence in the "galvanometer contact", so reviving the difficulty of sticking.

The electric mercury valve is a U-tube half filled with mercury. An iron cylinder N, floating on the mercury surface in one limb of the U-tube can be held and released by an electromagnet M. When N is released, the mercury surface in the limb will raise and close the mouth of the tube P, and when N is held the mercury will then open the mouth of P. This forms a valve. Above the mercury surface the pressure, which is different from that in F, is maintained by a reservoir R. The function of the capillary tube C' is to prevent the sudden rush of the gas.

Suppose that the pressure in the vacuum system A is gradually decreasing, A being connected to a diffusion pump. The "galvanometer contact" is then made. The action of the contact will open the mercury valve to increase the pressure. In this case R should have higher pressure than F. When the pressure is restored, the "galvanometer contact" breaks and the valve is then closed again. The method of measuring the speed of the diffusion pump is simply to record the change of pressure in R during a long time interval. For, assume the temperature constant and let P_1 = initial pressure, P_2 = final pressure, V = volume of R, t = time interval, P = pressure in vacuum system A. then the speed will be

$$S = \frac{(P_1 - P_2)V}{Pt}.$$

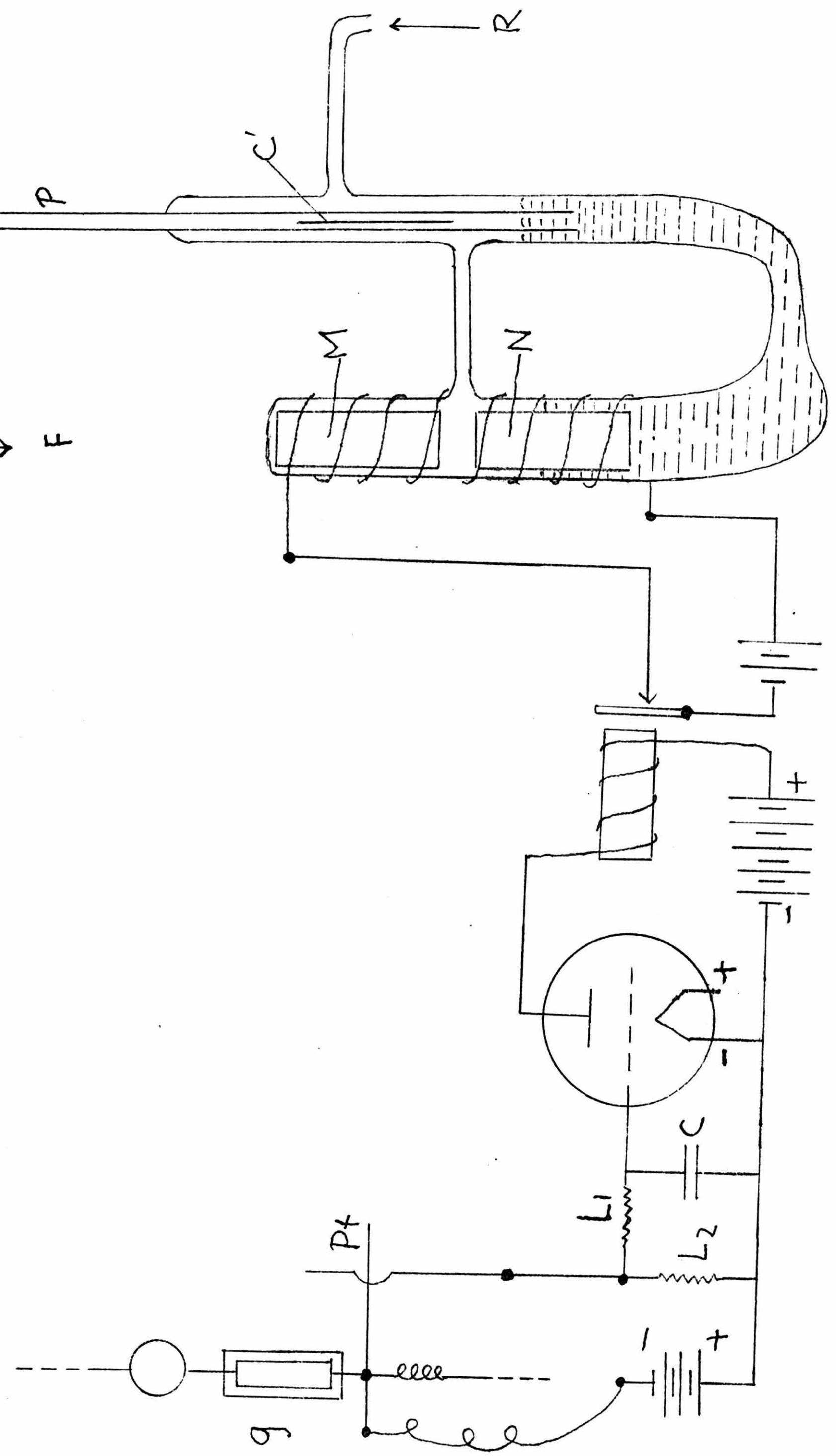

Fig 9

The higher the sensitivity of the gauge B, the smaller the magnitude of the fluctuation of the pressure in A would be.

For more accurate work, it is suggested that a selenium cell (or a photoelectric cell) be exposed to the image of a strongly illuminated source reflected at the galvanometer mirror, instead of using the platinum wire "galvanometer contact". The remaining part of the electric circuit is exactly the same. This is similar to Van den Akker's attachment[14] used in this laboratory.

APPENDIX II

Some Simple Vacuum Technique

1. To locate leak by two gauges:

In case a leak of a vacuum system can not be tested by spark coil, the following method is found to be applicable. Suppose two gauges a and b (Fig. 10) first connected at A and B of a vacuum system, pump working on the right-hand side of B, and consider that there must be a pressure gradient along

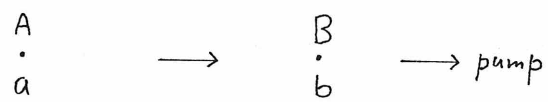

Fig 10

the path of the gas from the leak to the pump. Then: (a) if there is no pressure difference between A and B, the leak must be on the right-hand side of B; (b) if there is a pressure difference between A and B and if, on moving gauge a to the left-hand side of A, the pressure difference of the two gauges increases, the leak must be on the left-hand side of A; (c) if there is a pressure difference between A and B, and if, on moving gauge a to the left-hand side of A, there is no increasing of pressure difference of the two gauges, the leak must be between A and B.

2. To make an ordinary stop cock suitable for high vacuum use:

It is expensive to make specially a high vacuum stop cock as described by Travers (15) and by Trivelli (16). So, unless a large opening is needed, the ordinary stop cock is used to connect two vacuum systems. To prevent the entering of atmospheric air into the vacuum system, a glass ring (a short piece of glass tube) is sealed to its upper (larger) end for holding mercury, and a glass boss)a short glass tube with one end closed) is seàled to its lower (smaller) end, both being the same sizes as the corresponding ends. It is satisfactory that both are darefully sealed by hard sealing wax.

3. A rubber tube valve:

This simple valve is to regulate the admittion of the atmospheric air into a vacuum as in operating a shortened type McLeod gauge. Two pieces of short small glass tube, one with open end and one with closed end, are held together as shown in Fig. 11 by a piece of short thick-walled rubber tube with their ends 1 or 2 mm apart, thus forming a gap inside the rubber tube.

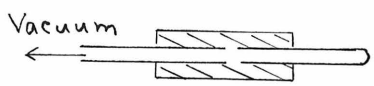

Fig 11

Around the gap, the rubber tube is pricked by a pin from outside to inside. The pricked holes are so small that, when the rubber tube is its natural length, a very small amount of gas can pass through them. When it is bent, the holes on the convex side are enlarged and this let the air in. So, the rate of air flowing in is easily regulated by hand.

4. An electric mercury valve:

This has been described in 2 of Appendix I. For ordinary use in transferring a small amount of gas from one vacuum system to another, this can be operated by a key in place of the relay.

5. A small McLeod gauge:

This simple McLeod gauge needs no calibration and needs little mercury, is used to measure the pressure of low vacuum from one atmosphere to a few thousandths of a mm. The only difference between this and a high vacuum McLeod gauge is that this has merely a glass tube "a" of uniform small bore (Fig. 12) instead of a large bulb and a fine capillary tube. The leading tube "b" is chosen to have the same size as "a".

Let p be the pressure to be measured. Then, from the diagram

$$pLA = (h+p)\,\ell A,$$

A being the area of the cross-section of a,

or $$p\cdot(L-\ell) = \ell h$$

$$\therefore \quad p = \frac{\ell h}{L-\ell}.$$

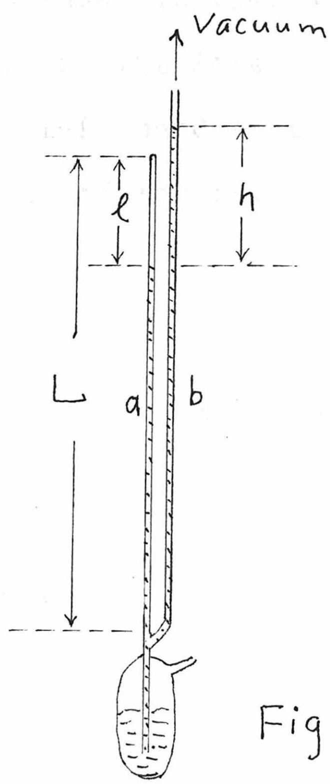

Fig 12

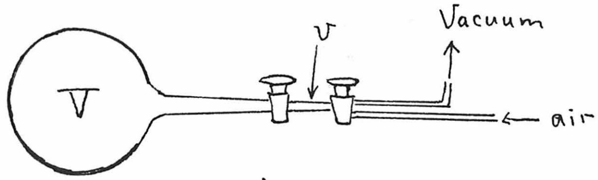

Fig 13

6. A pressure increaser:

A flask, a single way stop cock and a double way stop cock fused together as shown in Fig. 13 form a simple pressure increaser. For example; to increase the pressure of the vacuum system, the gas is first introduced into a small volume v, then its pressure is reduced by expanding it into a large volume V, finally letting this low pressure gas confined in v get into the vacuum system.

7. Heating current circuit breaker:

To prevent the burning up of the ionization gauge or hot wire gauge and the oxidation of the vapor of diffusion pump due to an accidental crack of the glass of the vacuum system, an automatic device to break the heating current circuit is provided. This is simply a V-shaped mercury manometer connected to the fore vacuum side of the pump system as shown in Fig. 14. The leak of a crack will increase the pressure of the fore vacuum side. Then the rise of mercury in the left-hand side limb of the manometer will complete the circuit of the relay and thus break the heating current circuits.

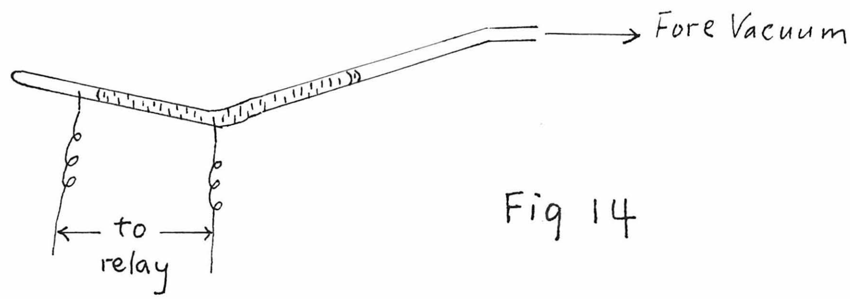

Fig 14

R E F E R E N C E S

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(13) Howard S. Roberts, J.O.S.A. & R.S .I. 11, (1925), P. 179.

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(15) Travers, The Experimental Study of Gases, P. 25, 1901.

(16) Trivelli, J.O.S.A. & R.S.I. 16, (1928), P. 367.

S U M M A R Y

It has not been possible to calculate theoretically the speed of the currently used diffusion pumps after Langmuir, because, unlike the Gaede's original type of diffusion pump, they have the vapor jet and the wide slit which prevent us from formulating the exact condition of the dispersed vapor through the so-called slit. The factors concerning the speed have been theoretically discussed and qualitatively verified by experiments. The experimental investigation is chiefly on the dependence of speed on vapor pressure, fore pressure, temperature of cooling system, kind of vapor used, kind of gas to be extracted, size of pump and form of jet; and the related experimental facts of previous workers are also discussed and referred to. Some of the results on speed can be stated definitely as follows: The speed is independent of the fore pressure when it is far from critical. The speed decreases as vapor pressure increases except at low vapor pressure, at which it has a maximum. The speed is nearly inversely proportional to the square root of the molecular weight of the gas to be extracted. The speed is independent of the pressure at which the pump works. As the temperature of the cooling system decreases the speed first increases and then reaches a constant. The speed of n-butyl phthalate vapor pump is greater than that of the mercury vapor pump. The speed of pump with divergent nozzle is greater than that with straight nozzle.