THE PARALLEL JET HIGH VACUUM PUMP

By William W. Crawford.

EFFORTS to make a vapor aspirator-ejector produce a high vacuum have met the difficulty that the jet, when surrounded by a high vacuum, disperses and refuses to entrain the gas. Gaede[1] overcame this difficulty by confining the vapor stream in a practically continuous wall, through a narrow slit in which the gas enters the vapor stream. Williams[2] constricts the stream at the point of entrainment, causing it to pass this point with an increased velocity and reduced pressure, and finds that the narrow slit can be practically dispensed with. He provides a water-cooled surface at the point of entrainment to condense the vapor which tends to pass into the vacuum space. Langmuir[3] investigated the conditions in this type of pump more thoroughly, and reached the conclusion that the cooled surface is the essential element; the constriction of the stream does not appear in Langmuir's pump. Langmuir holds the view that a jet necessarily must disperse in a vacuum, and utilizes the dispersing vapor (apparently the major portion of the jet) to urge the gas along a surface on which the vapor condenses, and into the remainder of the jet, which delivers the gas to the rough pump.

According to the kinetic theory of gases, the paths of molecules between collisions are substantially rectilinear. At very low pressures, these paths become limited only by the walls of the chamber.[4] If the molecules emanate from a point and condense upon the walls, the linear path becomes evident from the location of shadow patterns of obstacles in the chamber.[5] Wood[6] has shown by this method that a mercury jet may be produced which does not disperse materially in a high vacuum.

If the molecules in Wood's jet retain variegated velocities, it seems clear that the limiting density for the jet cannot be much higher than that for Knudsen's molecular flow, since the faster and slower molecules

[1] Annalen der Physik, 1915, p. 357.

[2] Phys. Rev., May, 1916, p. 583.

[3] Phys. Rev., July, 1916, p. 48, Jour. Frankl. Inst., Dec., 1916, General Electric Review, Dec., 1916. See also Knipp, Phys. Rev., April, 1917, p. 311, and Jones and Russell, Phys. Rev., Sept., 1917, p. 301.

[4] Knudsen, Ann. d. Phys., 4, 28, 1909, p. 75.

[5] Anthony, Trans. A. I. E. E., 11, 133, 1894.

[6] Phil. Mag., Aug., 1915.

would have to traverse the entire length of the jet without colliding with molecules which they are overtaking, or being overtaken by. Such a jet could exert little mechanical effect on a gas, the molecules of which would pass freely through the jet in any direction.

If, however, a jet can be produced in which the molecules are moving not only in parallel directions, but also with nearly equal velocities, then collisions should disappear between the vapor molecules, even if the density of the vapor is far above the limit for ordinary molecular flow. Moreover, if collisions do occur, the resultant velocities must also be nearly equal and parallel, since[1] only the direction of the relative velocity, and not the velocity of the common center of gravity of the two molecules, is altered by the collision. A gas molecule moving with the jet could enter it readily, but would be effectively prevented from returning

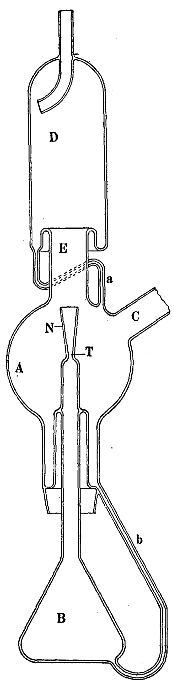

Fig. 1.

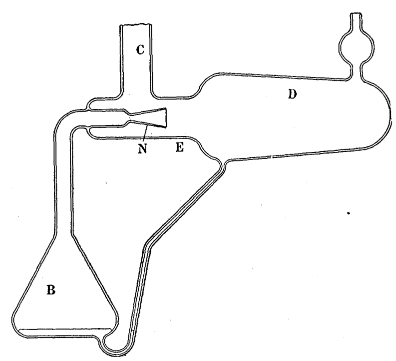

Fig. 2.

against the jet by the fact that it then meets a relatively enormous number of molecules, with some of which it must collide.

The line of thought indicated above led the author to try pumps of the form illustrated in Figs. 1 and 2. In Pump No. 6 (Fig. 1), the vapor generated in the boiler *B* at a pressure of 10 mm. of mercury or

[1] Maxwell, Scientific Papers, Vol. I, p. 377 et seq.

more, escapes through the narrow throat T, which, it will be noted, is at a considerable distance ahead of the point of entrainment. The vapor expands in the diverging nozzle N, and the issuing jet passes through the tube E, which it fills, and condenses in D, mostly, it is found, at the upper end. A slight amount of vapor escapes into the chamber A, and condenses there. The condensed vapor drains back through the tubes a and b, to the boiler. The gas to be pumped enters through C. Pump No. 5, Fig 2, is similar except as to arrangement, and the omission of the enlarged chamber A of Fig. 1, where its function is partly to condense the vapor arising from the mercury draining back from D.

The dimensions of the nozzle and passage E were about the same in the two pumps, viz.: Throat, 0.24 cm., mouth, 1.3 cm. diameter, ratio of areas, 30. Diameter of E, 2.5 cm., length, in No. 6, 5 cm., in No. 5 (measured from the end of N), 2.5 cm.

This form of nozzle is a result of the application of the principles of nozzle design used in steam engineering practice. As is well known, at the point of minimum area the pressure is never less than about half the initial pressure, the minimum pressure and maximum velocity occur in the diverging passage beyond the constriction. The reason for this difference from what takes place with a liquid lies in the expansive nature of the vapor.

It is found that a jet produced in this manner disperses only slightly, and will, if of a proper density, entrain the gas to be pumped even if the pressure of the gas is not over a thousandth of the computed internal pressure of the jet. No diffusion slit or condensing surface is necessary at the point of entrainment, in fact, the tube E surrounding the jet may be artificially heated to a point where no mercury can be seen condensing on it, without sensibly impairing the action. To all appearances the jet itself reëntrains and expels most of the vapor which is diffusely returned after striking the wall. The pumps are entirely air-cooled.

The theory of the formation of the jet appears to be that on account of the high initial pressure and the cooling due to the great ratio of expansion, the *relative* velocities of the molecules are much reduced, while they all acquire a very great common velocity in the direction of the jet. The absolute velocities are therefore nearly equal and parallel, as desired.

Certain properties of the jet in these pumps have been computed approximately, on the assumption that the vapor remains saturated, and neglecting friction, with the following results: Initial pressure, 18 mm., final pressure, 0.1 mm. Temperatures, 200 and 81° C., respectively. Velocity of jet, 42,000 cm. per sec. Relative molecular velocity, r.m.s. value, 21,000 cm. per sec. Mean free path, relative to jet, 0.08 cm.

If the free jet is 1 cm. long, each molecule is in it only 1/42,000 sec., in which time a molecule having the mean velocity will travel 0.5 cm. relative to the jet, and hence make only 6 collisions. Probably, due to the suddenness of the expansion and the absence of nuclei, the vapor enters the supersaturated condition, with a resultant lower temperature and lower relative molecular velocity, than that stated.

The fact that frictional effects do not destroy the jet suggests the explanation that the parallel motion reduces the number of collisions against the walls, both in the low pressure part of the nozzle, and in the compression passage E.

If the density of the jet exceeds a well-defined limit, the pump practically stops working, and the results approach those described by Langmuir for an aspirator with a dispersing jet. The author believes that this limit is established by the density of the dispersing fringe, which is probably proportional to the density of the jet, and occurs at the point where the mean free path of gas molecules entering the fringe becomes less than the total depth of the fringe.

TESTS.

In testing these pumps, the limitations of the apparatus available were such as to preclude obtaining extreme vacua. Pressures were measured on the intake side by a 500 c.c. McLeod gauge sealed to the pump through about 60 cm. of 1 cm. glass tubing, and on the discharge side by a 65 c.c. McLeod gauge, connected with glass tubing and rubber joints. The glass was not treated in any way, and the rate of fall of pressure, and the ultimate vacuum, were determined somewhat by the evolution from the glass and the friction in the tubing. The results were about the same with and without a drying agent (P_2O_5) in the vacuum space, the McLeod guage readings did not show symptoms of water vapor, indicating that the pump was effective in removing the latter.

The speed of the pump (cubic centimeters of gas per second at intake pressure) was determined by allowing air to leak in through a calibrated orifice located in the intake tube at a distance of 10 cm. from the pump, and was computed by the relation

$$S = \frac{760}{p} \times \frac{q}{1000},$$

where p = pressure in vacuum space, millimeters of mercury,

q = rate of leakage, cu. mm. per sec., measured at 760 mm. pressure.

The speed is therefore that of the pump in series with 10 cm. of tubing, 19 mm. in diameter.

Results.

Pump No.	Observation No.	Boiler Pressure, Mm.	Leakage, Cu. Mm. per Sec. *q*.	Pressure, Mm.		Speed C.c., *S*.
				Discharge.	Intake *p*.	
4	1	38	0	0.014	0.00002	——
	2	114	0	0.017	0.00004	——
	3	117	0	0.090	0.00002	——
	4	102	0.84	0.035	0.0061	105
	5	108	1.76	0.055	0.00105	1270
5	6	33	3.14	0.027	0.15	16
	7	27	2.0	0.024	0.11	16.5
	8	22	1.5	0.020	0.035	31.5
	9	21	1.6	0.019	0.013	93
	10	16	1.8	0.025	0.0025	550
	11	12	2.2	0.022	0.0026	640
	12	7	1.6	0.030	0.0021	580
	13	5	1.8	0.019	0.0029	470
	14	3	1.25	0.013	0.0058	164
	15	2	1.76	0.019	0.0086	155
	16	1	1.78	0.019	0.017	80
	17	16	0	0.057	0.00005	——
6	18	25	0	0.080	0.0001	——

Observations 6 to 16 inclusive are plotted in Fig. 3.

Pump No. 4 resembled No. 6 except that the nozzle had half the linear

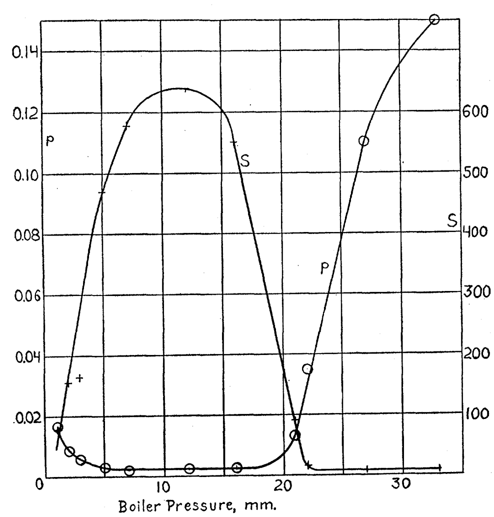

Fig. 3.

dimensions, and the chamber A was narrow, becoming heated by conduction and radiation from the vapor tube, and forcing the retrograde vapor to pass up into C before condensing. This was the condition in reading No. 4. A slight amount of cooling on A had the effect of greatly increasing the speed (reading 5). Cooling E as well as A gave little further increase in speed (perhaps 20 per cent.). Decreasing the radiation from E by wrapping it in cotton wool caused the mercury previously condensed on the wall to slowly reëvaporate, but while this was occurring the speed was not sensibly reduced. In readings 1 to 3 the pump was not cooled.

In all the readings given for No. 5, the passage E was electrically heated and no visible condensation took place in it. Even without this heating, relatively little mercury condenses here, but it was desired to prove that condensation was not a factor in the entrainment. These readings show clearly the necessity of the jet density lying within well-defined but not necessarily narrow limits. The ratio of expansion being fixed by the nozzle, the density of the jet may be considered as proportional to the boiler pressure. Simultaneously with the reduction of the speed by high boiler pressure, retrograde vapor could be seen condensing rapidly in C. The effect of too low density is also shown.

Only meager tests were made on No. 6, which was connected to the apparatus through narrow rubber tubing, preventing a favorable determination of the speed. This pump seemed to produce good results with a slightly higher boiler pressure than No. 5, indicating the usefulness of chamber A in rarefying and condensing the retrograde vapor, permitting the gas to be entrained despite the higher jet density.

The following comparison of the speed of these pumps with the values stated by Langmuir for the condensation pump is of interest.

Style.	Diameter, Cm.	Speed, C.c. per Sec.	Ratio Speed/Diam.^{2}.
Condensation	2.0	200	50
Parallel jet No. 5	2.5	500	80
Parallel jet No. 4	2.5	1200	192
Condensation	7.0	3000	61

It is probable that the jets in Nos. 4 and 5 are not the best that can be produced by this method, and that with slightly different proportions, greater speeds can be obtained with tubing of the same size. The speed of the intake passages of No. 5, computed by Knudsen's formula, is about 5,000 c.c. per sec., the difference is to be attributed to the resistance of the jet to the entrainment of the gas.

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