to their surfaces. Hence iron filings, if carefully sprinkled on water, will not be wetted, but will float on the surface, and hence also the power which many insects have of running on the surface of water without wetting their feet. The film of air in these cases prevents wetting, and hence, by the principles of capillarity, produces increased buoyancy.

CHAPTER XX.

AIR-PUMP.

229. Air-pump.—The air-pump was invented by Otto Guericke about 1650, and has since undergone some improvements in detail which have not altered the essential parts of its construction.

Fig. 130 represents the pattern most commonly adopted in France. It contains a glass or metal cylinder called the barrel, in which a piston works. This piston has an opening through it which is closed at the lower end by a valve S opening upwards. The barrel communicates with a passage leading to the centre of a brass surface carefully polished, which is called the *plate* of the air-pump. The entrance to the passage is closed by a conical stopper S′, at the extremity of a metal rod which passes through the piston-head and works in it tightly, so as to be carried up and down with the motion of the piston. A catch at the upper part of the rod confines its motion within very narrow limits, and only permits the stopper to rise a small distance above the opening.

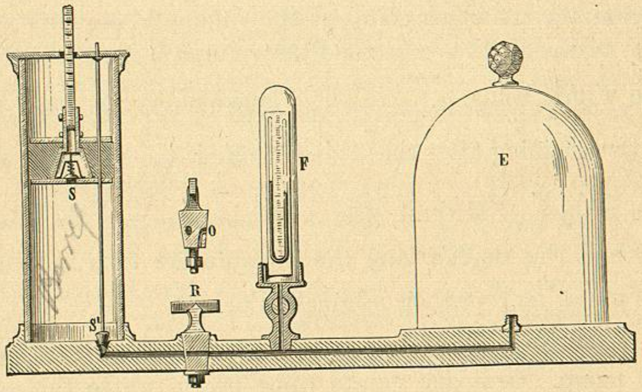

Fig. 130.—Air-pump

$P_n = P\left(\frac{V}{V+v}\right)^n$

Suppose now that the piston is at the bottom of the cylinder, and is raised. The valve S′ is opened, and air from the receiver E rushes into the cylinder. On lowering the piston, the valve S′ closes its opening, the air which has entered the cylinder cannot return into the receiver, and, on being compressed, raises the valve S in the piston, and escapes into the air outside. On raising the piston again, a portion of the air remaining in the receiver will pass into the cylinder, whence it will escape on pushing down the piston, and so on.

We see, then, that if this motion be continued, a fresh portion of the air in the receiver will be removed at each successive stroke. But as the quantity of air removed at each stroke is only a fraction of the quantity which was in the receiver at the beginning of the stroke, we can never produce a perfect vacuum, though we might approach as near to it as we pleased if this were the only obstacle.

230. Theoretical Rate of Exhaustion.—It is easy to calculate the quantity of air left in the receiver after a given number of strokes of the piston. Let V be the volume of the barrel, V′ that of the receiver, and M the mass of air in the receiver at first. On raising the piston, the air which occupied the volume V′ occupies a volume $V' + V$; of the air thus expanded the volume V is removed, and the volume V′ left, being $\frac{V'}{V'+V}$ of the whole quantity or mass M. The quantity remaining after the second stroke is $\frac{V'}{V'+V}$ of that after the first, or is $\left(\frac{V'}{V'+V}\right)^2 M$; and after n strokes $\left(\frac{V'}{V'+V}\right)^n M$. Hence the density and (by Boyle's law) the pressure are each reduced by n strokes to $\left(\frac{V'}{V'+V}\right)^n$ of their original values.

This calculation gives the theoretical rate of exhaustion for a perfect pump. Ordinary pumps come nearly up to this standard during the earlier part of the process of exhaustion; but as further progress is made, the imperfections of the apparatus become more sensible, and set a limit to the exhaustion attainable.

231. Mercurial Gauges.—To enable the operator to observe the progress of the exhaustion, the instrument is usually provided with a mercurial gauge. Sometimes, as in Fig. 130, this consists of a short siphon-barometer, the difference of levels between its two columns being the measure of the pressure in the receiver. Another plan is to have a straight tube open at both ends, and more than 30 inches long; its upper end being connected with the receiver, while its lower end dips into a cistern of mercury. As exhaustion proceeds, the mercury rises in this tube, and its height above the mercury in the cistern measures the difference between the pressure in the receiver and that in the external air.

232. Admission Stop-cock.—After the receiver has been exhausted of air, if it were required to raise it from the plate, a very considerable force would be necessary, amounting to as many times fifteen pounds as the base of the receiver contained square inches. This difficulty is obviated by having an admission stop-cock R, which is shown in section above. It is perforated by a straight channel, which, when the machine is being worked, forms part of the communicating passage. At 90° from the extremities of this channel is another opening O, forming the mouth of a bent passage, leading to the external air. When we wish to admit the air into the receiver, we have only to turn the stop-cock so as to bring the opening O to the side next the receiver; if, on the contrary, we turn it towards the pump-barrel, all communication between the pump and the receiver is stopped, the risk of air entering is diminished, and the vacuum remains good for a greater length of time. This precaution is taken when we wish to leave bodies in a vacuum for a considerable time. Another method is to employ a separate plate, which can be detached so as to leave the machine available for other purposes.

233. Double-barrelled Air-pump.—The machine just described has only a single pump-barrel; air-pumps of this kind are sometimes employed, and are usually worked by a lever like a pump-handle. With this arrangement, it is evident that no air is expelled in the down-stroke; and that the piston, after having expelled the air from the barrel in the up-stroke, must descend idle in order to prepare for the next stroke.

Double-barrelled pumps are more frequently used. An idea of their general arrangement may be formed from Figs. 131, 132, and 133. Fig. 133 gives the machine in perspective, Fig. 131 is a section through the axes of the pump-barrels, and Fig. 132 shows the manner in which communication is established between the receiver and the two barrels. It will be observed that the two passages from the barrels unite in a single passage to the centre of the plate p.

Two racks carrying the pistons CC work with the pinion P. This pinion is turned by a double-handed lever, which is moved alternately in opposite directions. In this arrangement, when one piston ascends the other descends, and consequently in each single stroke the air of the receiver passes into one or other pump-barrel. A vacuum is thus produced by half the number of strokes which would be required with a single-barrelled pump. It has besides another advantage, as compared with the single-barrelled pump above described. In that pump the force required to raise the piston increases as the exhaustion proceeds, and when it is nearly completed there is the resistance of almost an atmosphere to be overcome. In the double-barrelled pump, with the same construction of barrel, the force opposing the ascent of one piston is precisely equal, at the beginning of each stroke, to that which assists the descent of the other. This equality, however, exists only at the beginning of the stroke; for the air below the descending piston is compressed, and its tension increases till it becomes equal to that of the atmosphere and raises the piston valve. During the remainder of the stroke, the resistance to the ascent of the other piston is entirely uncompensated, and up to this point the compensation has been gradually diminishing. But the more nearly we approach to a perfect vacuum, the later in the stroke does this compensation occur.

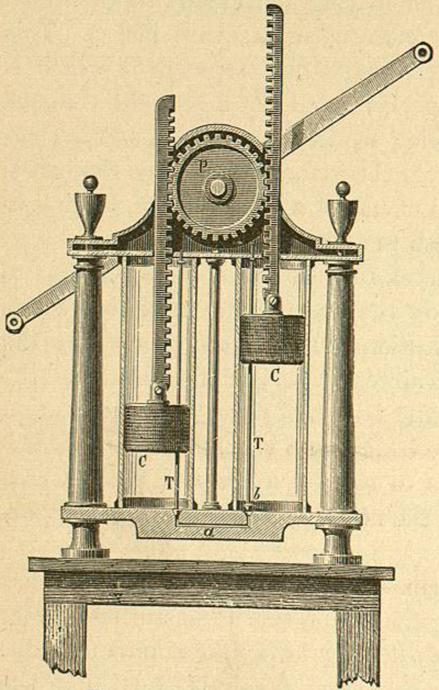

Fig. 131.

Double-barrelled Air-pump.

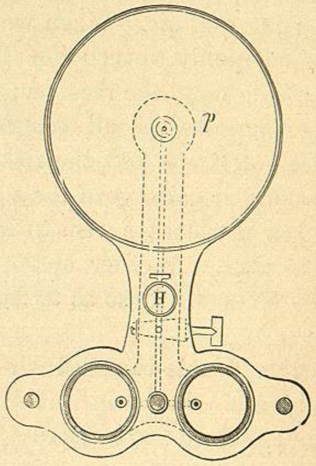

Fig. 132.

The pump, accordingly, becomes easier to work as the exhaustion proceeds.

234. Single-barrelled Pumps with Double Action.—We do not, however, require two pump-barrels in order to obtain double action, as the same effect may be obtained with a single barrel. An arrangement for this purpose was long ago suggested by Delahire for water-pumps; but the principle has only lately been applied to the construction of air-pumps.

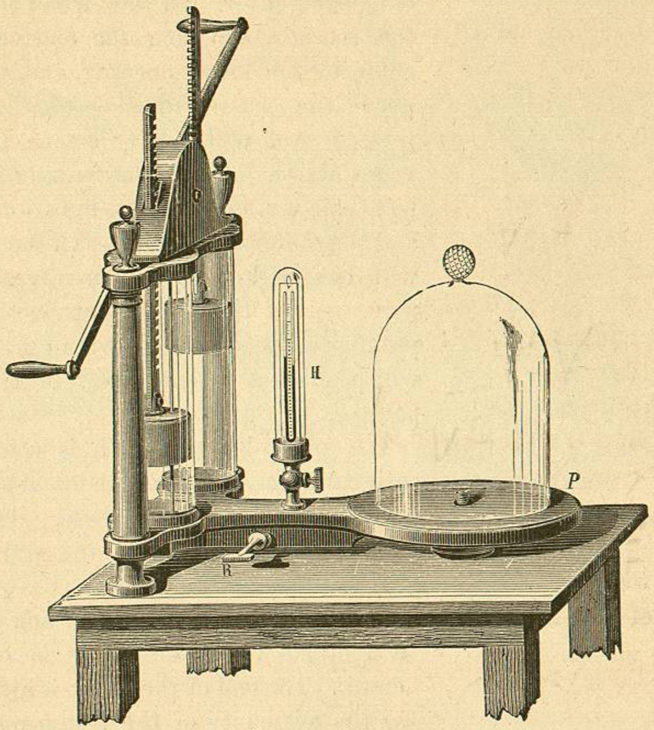

Fig. 133.—Air-pump.

Fig. 134 represents the single barrel of the double-acting pump of Bianchi. It will be seen that the piston-valve opens into the hollow piston-rod; a second valve, also opening upwards, is placed at the top of the pump-barrel. Two other openings, one above, the other below, serve to establish communication, by means of a bent vertical tube, between the pump-barrel and the passage to the plate. These openings are closed alternately by two conical stoppers at the two extremities of a metal rod passing through the piston, and carried with it in its vertical movement by means of friction. When the piston ascends, as in the figure, the upper opening is closed and the lower one is open; when the piston begins to descend, the opposite effect is immediately produced. Accordingly we see that, whichever be the direction in which the piston is moving, the receiver is being exhausted of air. In fact, when the piston ascends, air from the receiver will enter by the lower opening, and the air above the piston will be gradually compressed, and will finally escape by the valve above. In the descending movement, air will enter by the upper opening, and the compressed air beneath the piston will escape by the piston-valve. The movement of the piston is produced by a peculiar arrangement shown in Fig. 135, which gives a general view of the apparatus.

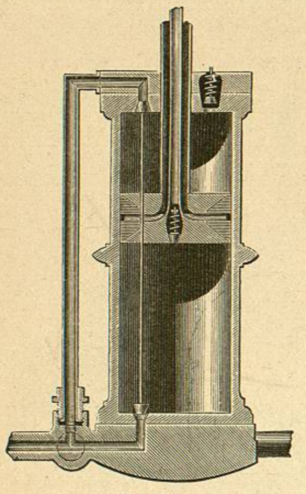
Fig. 134.
Barrel of Bianchi's Air-pump.

The pump-barrel, which is composed entirely of cast-iron, oscillates about an axis passing through its base. On the top are guides in which the end of a crank travels. The pump is worked by turning a heavy fly-wheel of cast-iron, on the axis of which is a pinion which drives a toothed wheel on the axis of the crank. The end of the crank is attached to the extremity of the piston-rod. It is evident that on turning the fly-wheel the pump-barrel will oscillate from side to side, following the motions of the crank, and the piston will alternately ascend and descend in the barrel, the length of which should be equal to the diameter of the circle described by the end of the crank.

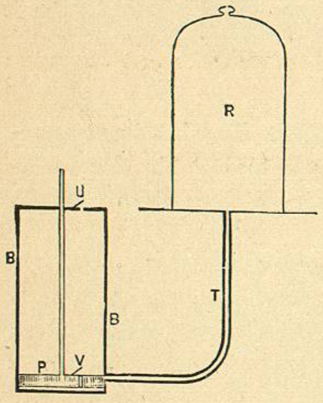

Fig. 136

235. English forms of Air-pump.—Some of the drawbacks to the single-barrelled pump are obviated by inserting a valve, opening upwards, in the top of the barrel as at U, Fig. 136. The top of the piston is thus relieved from atmospheric pressure, and the operation of pumping does not become more laborious as

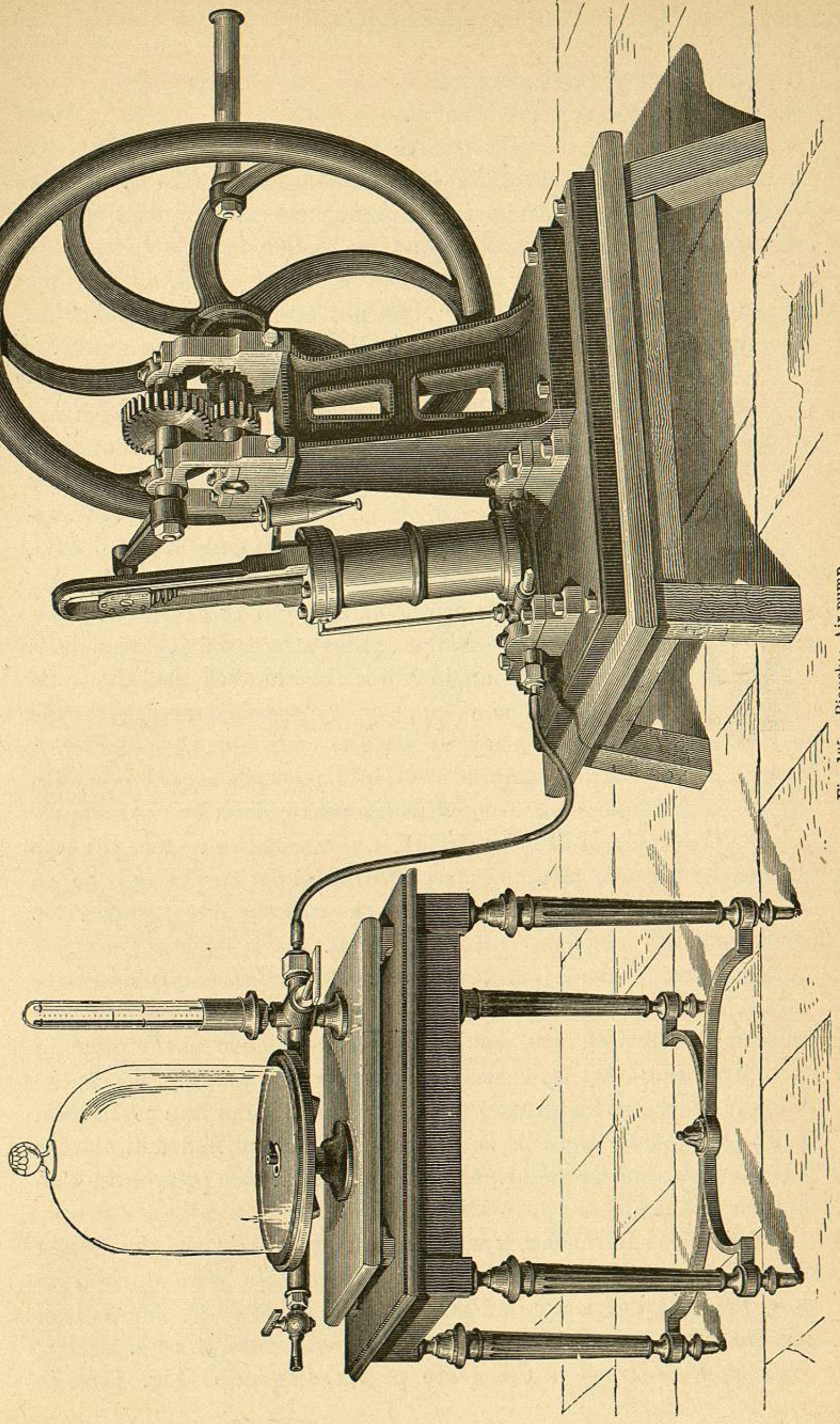
Fig. 135.—Bianchi's Air-pump.

the exhaustion proceeds, but less laborious, the difference being most marked when the receiver is small.

In the up-stroke, the piston-valve V keeps shut, and the air above the piston is pushed out of the barrel through the valve U. In the down-stroke, U is kept closed by the preponderance of atmospheric pressure outside, and V opens, allowing the air to pass up through it as the piston descends to the bottom of the barrel. When the exhaustion is far advanced, U does not open till the piston has nearly reached the top. This is a simple and good form of pump.

Another form very much in use in this country is the double-acting pump of Professor T. Tate, the working parts of which are shown in Fig. 137. CD is the barrel; A and B are two solid pistons rigidly connected by a rod, and moved by the piston-rod AH, which passes through a stuffing-box S. VV are valves in the two ends of the barrel, both opening outwards, and R is a passage leading from the middle of the cylinder to the receiver. The distance between the extreme faces of the pistons is about ⅜ths of an inch less than half the length of the cylinder. The volume of air expelled at each single stroke is thus about half the volume of the cylinder.

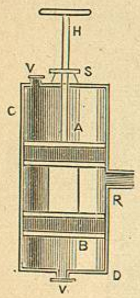

Fig. 137.
Tate's Pump.

This figure and description are in accordance with the original account of the pump given by the inventor in the *Philosophical Magazine.* It is now usual to replace the two pistons by a single piston of great thickness, its two faces being as far apart as the extreme faces of the two pistons in the figure. It is also usual to make the barrel horizontal.

The valves of these pumps, and of most English pumps are "silk valves." They consist of a short and narrow slit in a thin plate of brass, with a flap of oiled silk secured at both ends to the plate, in such a position that its central portion covers the slit. When the pressure of the air is greater on the further side of the plate than on the side where the silk is, the flap is slightly lifted and the air gets through; but excess of pressure on the near side presses the flap down over the slit and makes it air-tight.

236. Various Experiments with the Air-pump.—At the time when the air-pump was invented, several experiments were devised to show the effects of a vacuum, some of which have become classical, and are usually repeated in courses of experimental physics.

Burst Bladder.—On the plate of an air-pump (Fig. 138) is placed a glass cylinder open at the bottom, and having a piece of bladder or thin indian-rubber tightly stretched over the top. As the exhaustion proceeds, this bends inwards in consequence of the atmospheric pressure above it, and finally bursts with a loud report.

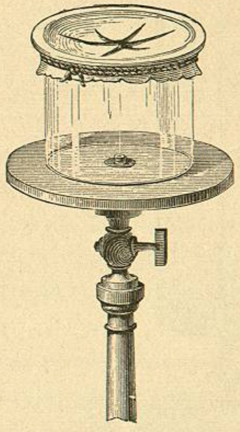

Fig. 138.
Burst Bladder.

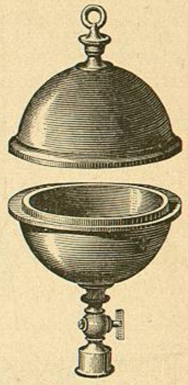

Fig 139.
Magdeburg Hemisphere.

Magdeburg Hemispheres.—We take two hemispheres (Fig. 139), which can be exactly fitted on each other; their exact adjustment is further assisted by a projecting internal rim, which is smeared with lard. The apparatus is exhausted of air through the medium of the stop-cock attached to one of the hemispheres; and when a vacuum has been produced, it will be found that a considerable force is required to separate the two parts, this force increasing with the size of the hemispheres.

This resistance to separation is due to the normal exterior pressure of the air on every point of the surface, a pressure which is counterbalanced by only a very feeble pressure from the interior. In order to estimate the resultant effect of these different pressures, let us suppose that one hemisphere is vertically over the other, and that the external surface is cut into a series of steps,—that is to say, of alternate vertical and horizontal elements. It is evident that the pressure urging either hemisphere towards the other will be simply the sum of the pressures upon its horizontal elements; and this sum is identical with the pressure which would be exerted upon a circular area equal to the common base of the hemispheres. For example, if this area is 10 square inches, and the external pressure exceeds the internal by 14 lbs. to the inch, the hemispheres will be pressed together with a force of 140 lbs.

Fountain in Vacuo.—The apparatus for this experiment consists of a bell-shaped vessel of glass (Fig. 140), the base of which is pierced by a tube fitted with a stop-cock which enables us to exhaust the vessel of air. If, after a vacuum has been produced, we place the lower end of the tube in a vessel of water, and open the stop-cock, the liquid, being pressed externally by the atmosphere, mounts up the tube and ascends in a jet into the interior of the vessel. This experiment is often made in the opposite manner. Under the receiver of the air-pump is placed a vial partly filled with water, and having its cork pierced by a tube open at both ends, the lower end being beneath the surface of the water. As the exhaustion proceeds, the air in the vial, by its excess of pressure, acts upon the liquid and makes it issue in a jet.

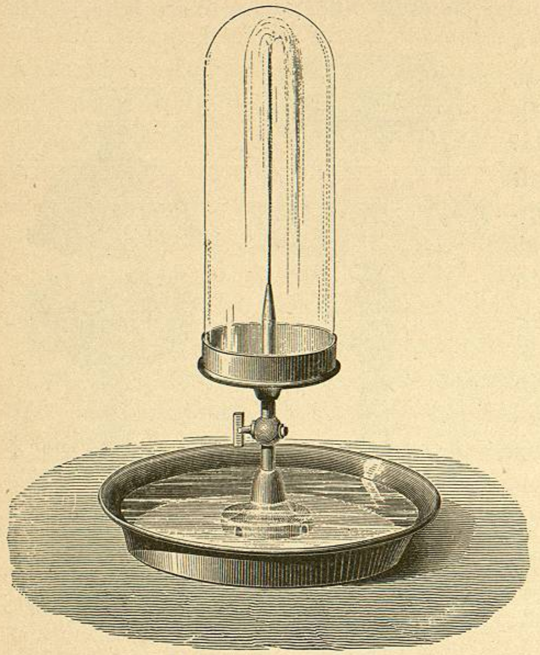

Fig. 140.—Fountain in Vacuo.

237. Limit to the Action of the Air-pump.—We have said above (§ 230) that the air-pump does not continue the process of rarefaction indefinitely, but that at a certain stage its effect ceases, and the pressure of the air in the receiver undergoes no further diminution. If the pump is very badly made, this pressure is considerable; but even with the most perfect machines it is always sensible. A pump such as we have described may be considered good if it reduces the pressure of the air in the receiver to a tenth of an inch of mercury. A fiftieth of an inch is perhaps the lowest limit.

Leakage.—This limit to the action of the machine is due to various causes. In the first place, there is frequently leakage at different parts of the apparatus; and although at the beginning of the operation the quantity of air which thus enters is small in comparison with that which is pumped out, still, as the exhaustion proceeds, the air enters faster, on account of the diminished internal pressure, and at the same time the quantity expelled at each stroke becomes less, so that at length a point is reached at which the inflow and outflow are equal.

In order to prevent leakage as far as possible, the plate of the pump and the base of the receiver must be truly plane so as to fit accurately; the base of the receiver must be ground (that is roughened) and must be well greased before pressing it down on the plate. The piston must also be well lubricated with oil.

Space untraversed by Piston.—Another reason of imperfect exhaustion is that, after all possible precautions, a space is still left between the bottom of the pump-barrel and the lower surface of the piston when the latter is at the end of its downward stroke. It is evident that at this moment the air contained in this *untraversed space* is of the same tension as the atmosphere. On raising the piston, this air is indeed rarefied; but it still preserves a certain tension, and it is evident that when the air in the receiver has been brought to this stage of rarefaction, the machine will cease to produce any effect.

If v is the volume of this space, and V the volume of the pump-barrel, the air, which at volume v has a pressure H equal to that of the atmosphere, will have, at volume V, a pressure $H\frac{v}{V}$. This gives the limit to the action of the machine as deduced from the consideration of the untraversed space.

Air given out by Oil.—Finally, perhaps the most important cause, and the most difficult to remedy, is the absorption of air by the oil used for lubricating the pistons. This oil is poured on the top of the piston, but the pressure of the external air forces it between the piston and the barrel, whence it falls in greater or less quantity to the bottom of the barrel, where it absorbs air, and partially yields it up at the moment when the piston begins to rise, thus evidently tending to derange the working of the machine. It has been attempted to get rid of untraversed space by employing a kind of piston of mercury. This has also the advantage of fitting the barrel more accurately, and thus preventing the entrance of air. The use of oil is at the same time avoided, and we thus escape the injurious effects mentioned above. We proceed to describe two machines founded upon this principle.

238. Kravogl's Air-pump.—This contains a hollow glass cylinder AB (Fig. 141) tapering at the upper end, and surmounted by a kind of funnel. The piston is of the same shape as the cylinder, and is covered with a layer of mercury, whose depth over the point of the piston is about $\frac{1}{50}$th of an inch when the piston is at the bottom of its stroke, but is nearly an inch when the piston rises and fills the funnel-shaped cavity in which the pump-barrel terminates. A small interval, filled by the liquid, is left between the barrel and the piston; but at the bottom of the barrel the piston passes through a leather box carefully made, so as to be perfectly air-tight.

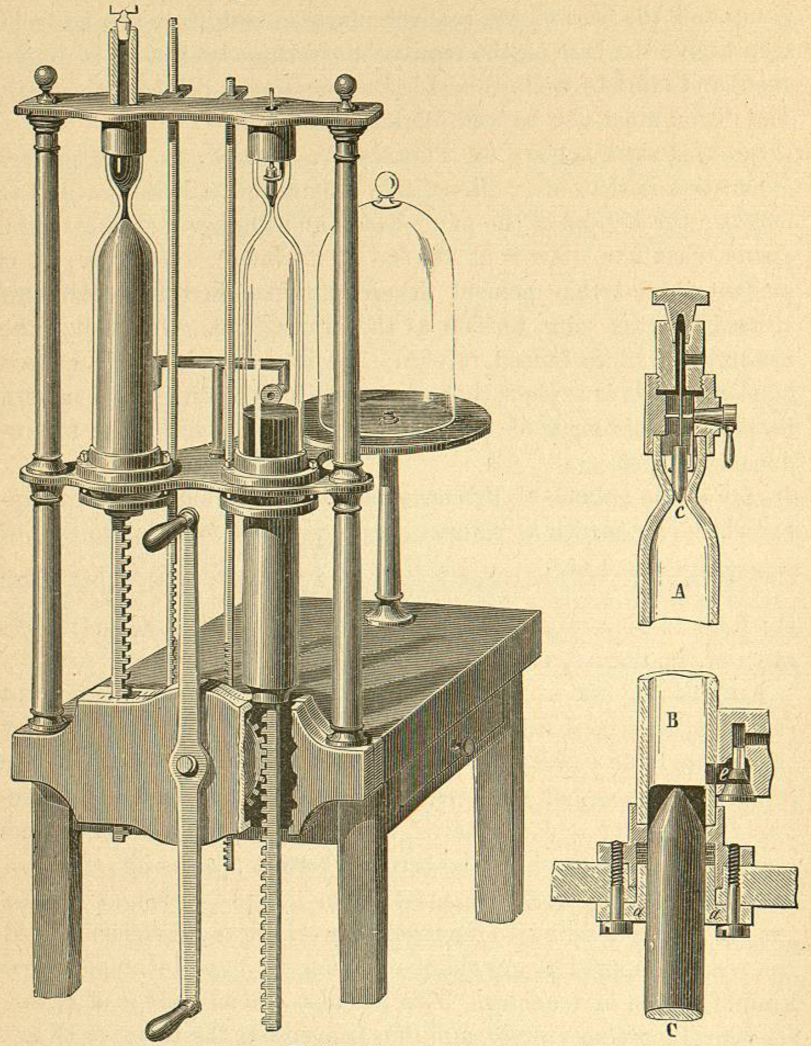

Fig. 141.—Kravogl's Air-pump.

The air from the receiver enters through the lateral opening *e*, and is driven before the mercury into the funnel above. With the air passes a certain quantity of mercury, which is detained by a steel valve *c* at the narrowest part of the funnel. This valve rises automatically when the surface of the mercury is at a distance of about half an inch from the funnel, and falls back into its former position when the piston is at the end of its upward stroke. In the downward stroke, when the mercury is again half an inch from the funnel. the valve opens again and allows a portion of the mercury to pass.

The effect of this arrangement is easily understood; there is no "untraversed space," the presence of the mercury above and around the piston causes a very complete fit, and excludes the external air; and hence the machine, when well made, is very effective.

When this is the case, and when the mercury used in the apparatus is perfectly dry, a vacuum of about $\frac{1}{250}$th of an inch can be obtained. The dryness of the mercury is a very important condition, for at ordinary temperatures the elastic force of the vapour of water has a very sensible value. If we wish to employ the full powers of the machine, we must have, between the vessel to be exhausted of air and the pump-barrel, a desiccating apparatus.

The arrangement of the valve *e* is peculiar. It is of a conical form, so as, in its lowest position, to permit the passage of air coming from the receiver. Its ascent is produced by the pressure of the mercury, which forces it against the conical extremity of the passage, and the liquid is thus prevented from escaping.

The figure represents a double-barrelled machine analogous to the ordinary air-pump. Besides the pinion working with the racks of the pistons, there is a second smaller pinion, not shown in the figure, which governs the movements of the valves *c*. All the parts of this machine, as the stop-cocks, valves, pipes, &c., must be of steel, to avoid the action which the mercury would have upon any other metal.

239. Geissler's Machine.—Geissler, of Bonn, invented a mercurial air-pump, in which the vacuum is produced by communication of the receiver with a Torricellian vacuum. Fig. 142 represents this machine as constructed by Alvergniat. It consists of a vertical tube, serving as a barometric tube, and communicating at the bottom, by means of a caoutchouc tube, with a globe which serves as the cistern.

At the top of the tube is a three-way stop-cock, by which communication can be established either with the receiver to the left, or