that of the weights used, the real weight is greater than the apparent weight; if the contrary, the case is reversed. If the body to be weighed were of the same density as the weights used, the real and apparent weights would be equal. We may remark, that in determining the *ratio* of the weights of two bodies of the same density, by means of standard weights which are all of one material, we need not concern ourselves with the effect of the upward pressure of the air; as the correcting factor, which has the same value for both cases, will disappear in the quotient.

CHAPTER XXII.

PUMPS FOR LIQUIDS.

252. Machines for raising water have been known from very early ages, and the invention of the common pump is pretty generally ascribed to Ctesibius, teacher of the celebrated Hero of Alexandria; but the true theory of its action was not understood till the time of Galileo and Torricelli.

253. **Reason of the Rising of Water in Pumps.**—Suppose we take a tube with a piston at the bottom (Fig. 154), and immerse the lower end of it in water. The raising of the piston tends to produce a vacuum below it, and the atmospheric pressure, acting upon the external surface of the liquid, compels it to rise in the tube and follow the upward motion of the piston. This upward movement of the water would take place even if some air were interposed between the piston and the water; for on raising the piston, this air would be rarefied, and its pressure no longer balancing that of the atmosphere, this latter pressure would cause the liquid to ascend in a column whose weight, added to the pressure of the air below the piston, would be equal to the atmospheric pressure. This is the principle on which water rises in pumps. These instruments have a considerable variety of forms, of which we shall describe the most important types.

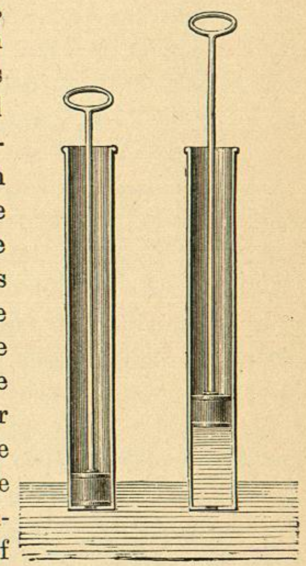

Fig. 154.—Principle of Suction-pump.

254. **Suction-pump.**—The suction-pump (Fig. 155) consists of a

cylindrical pump-barrel traversed by a piston, and communicating by means of a smaller tube, called the suction-tube, with the water in the pump-well. At the junction of the pump-barrel and the tube is a valve opening upward, called the suction-valve, and in the piston is an opening closed by another valve, also opening upward.

Suppose now the suction-tube to be filled with air at the atmospheric pressure, and the water consequently to be at the same level inside the tube and in the well. Suppose the piston to be at the end of its downward stroke, and to be now raised. This motion tends to produce a vacuum below the piston, hence the air contained in the suction-tube will open the suction-valve, and rush into the pump-barrel. The elastic force of this air being thus diminished, the atmospheric pressure will cause the water to rise in the tube to a height such that the pressure due to this height, increased by the pressure of the air inside, will exactly counterbalance the pressure of the atmosphere. If the piston now descends, the suction-valve closes, the water remains at the level to which it has been raised, and the air, being compressed in the barrel, opens the piston-valve and escapes. At the next stroke of the piston, the water will rise still further, and a fresh portion of air will escape.

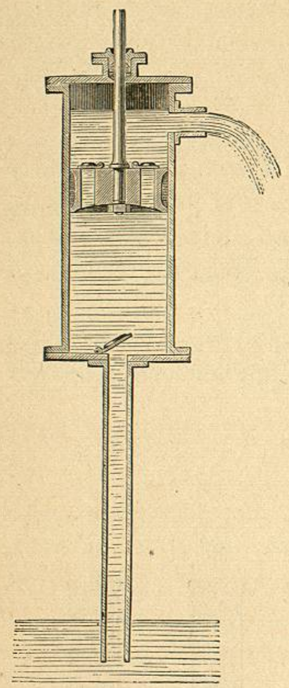

Fig. 155.—Suction-pump.

If, then, the length of the suction-tube is less than about 30 feet, the water will, after a certain number of strokes of the piston, be able to reach the suction-valve and rise into the pump-barrel. When this point has been reached the action changes. The piston in its downward stroke compresses the air, which escapes through it, but the water also passes through, so that the piston when at the bottom of the pump-barrel will have above it all the water which has previously risen into the barrel. If the piston be now raised, supposing the total height to which it is raised to be not more than 34 feet above the level of the water in the well, as should always be the case, the water will follow it in its upward movement, and will fill the

pump-barrel. In the downward stroke this water will pass up through the piston-valve, and in the following upward stroke it will be discharged at the spout. A fresh quantity of water will by this time have risen into the pump-barrel, and the same operations will be repeated.

We thus see that from the time when the water has entered the pump-barrel, at each upward stroke of the piston a volume of water is ejected equal to the contents of the pump-barrel.

In order that the water may be able to rise into the pump-barrel, the suction-valve must not be more than 34 feet above the level of the water in the well, otherwise the water would stop at a certain point of the tube, and could not be raised higher by any farther motion of the piston.

Moreover, in order that the working of the pump may be such as we have described, that is, that at each upward stroke of the piston a quantity of water may be removed equal to the volume of the pump-barrel, it is necessary that the piston when at the top of its stroke should not be more than 34 feet above the water in the well.

255. Effect of untraversed space.—If the piston does not descend to the bottom of the barrel, it is possible that the water may fall short of rising to the suction-valve, even though the total height reached by the piston be less than 34 feet. When the piston is at the end of its downward stroke, the air below it in the barrel is at atmospheric pressure; and when the limit of working has been reached, this air will expand during the upward stroke until it fills the barrel. Its pressure will now be the same as that of the air in the top of the suction-tube; and if this pressure be equivalent to h feet of water, the height to which water can be drawn up will be only $34-h$ feet.

Example. The suction-valve of a pump is at a height of 27 feet above the surface of the water, and the piston, the entire length of whose stroke is 7·8 inches, when at the lowest point is 3·1 inches from the fixed valve; find whether the water will be able to rise into the pump-barrel.

When the piston is at the end of its downward stroke, the air below it in the barrel is at the atmospheric pressure; when the piston is raised this air becomes rarefied, and its pressure, by Boyle's law, becomes $\frac{3·1}{10·9}$ that of the atmosphere; this pressure can therefore balance a column of water whose height is $34 \times \frac{3\cdot1}{10\cdot9}$ feet, or 9·67 feet. Hence, the maximum height to which the water can attain is $34 - 9\cdot67$ feet $= 24\cdot33$ feet; and consequently, as the suction-tube is 27 feet long, the water will not rise into the pump-barrel, even supposing the pump to be perfectly free from leakage.

Practically, the pump-barrel should not be more than about 25 feet above the surface of the water in the well; but the spout may be more than 34 feet above the barrel, as the water after rising above the piston is simply pushed up by the latter, an operation which is independent of atmospheric pressure. Pumps in which the spout is at a great height above the barrel are commonly called *lift-pumps*, but they are not essentially different from the suction-pump.

256. Force necessary to raise the Piston.—The force which must be expended in order to raise the piston, is equal to the weight of a column of water, whose base is the section of the piston, and whose height is that to which the water is raised. Let S be the section of the piston, P the atmospheric pressure upon this area, h the height of the column of water which is above the piston in its present position, and h' the height of the column of water below it; then the upper surface of the piston is subjected to a pressure equal to $P + Sh$; the lower face is subjected to a pressure in the opposite direction equal to $P - Sh'$, and the entire downward pressure is represented by the difference between these two, that is, by $S(h + h')$.

The same conclusion would be arrived at even if the water had not yet reached the piston. In this case, let l be the height of the column of water raised; then the pressure below the piston is $P - Sl$; the pressure above is simply the atmospheric pressure P, and, consequently, the difference of these pressures acts downward, and its value is Sl.

257. Efficiency of Pumps.—From the results of last section it follows that the force required to raise the piston, multiplied by the height through which it is raised, is equal to the weight of water discharged multiplied by the height of the spout above the water in the well. This is an illustration of the principle of work (§ 49). As this result has been obtained from merely statical considerations, and on the hypothesis of no friction, it presents too favourable a view of the actual efficiency of the pump.

Besides the friction of the solid parts of the mechanism, there is work wasted in generating the velocity with which the fluid, as a whole, is discharged at the spout, and also in producing eddies and other internal motions of the fluid. These eddies are especially produced at the sudden enlargements and contractions of the passages through which the fluid flows. To these drawbacks must be added loss from leakage of water, and at the commencement of the operation from leakage of air, through the valves and at the circumference of the piston. In common household pumps, which are generally roughly made, the *efficiency* may be as small as ·25 or ·3; that is to say, the product of the weight of water raised, and the height through which it is raised, may be only ·25 or ·3 of the work done in driving the pump.

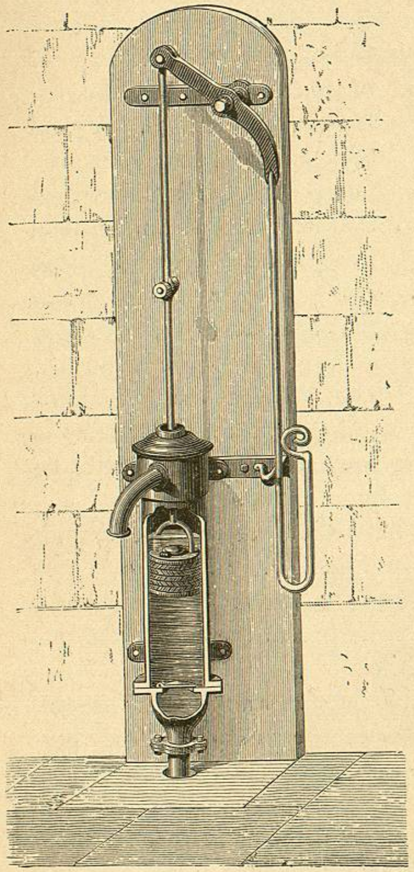

Fig. 156.

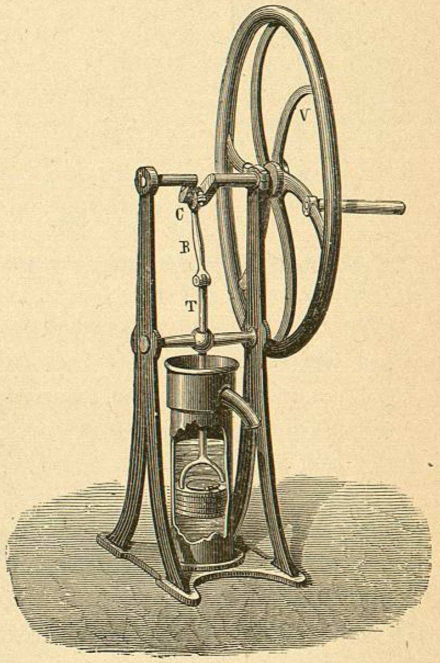

Fig. 157.

Suction-pump.

In Figs. 156 and 157 are shown the means usually employed for working the piston. In the first figure the upward and downward movement of the piston is effected by means of a lever. The second figure represents an arrangement often employed, in which the alternate motion of the piston is effected by means of a rotatory motion. For this purpose the piston-rod T is joined by means of the connecting-rod B to the crank C of an axle turned by a handle attached to the fly-wheel V.

258. Forcing-pump.—The forcing-pump consists of a pump-barrel dipping into water, and having at the bottom a valve opening upward. In communication with the pump-barrel is a side-tube, with a valve at the point of junction, opening from the barrel into the tube. A solid piston moves up and down the pump-barrel, and it is evident that when this piston is raised, water enters the barrel by the lower valve, and that when the piston descends, this water is forced into the side-tube. The greater the height of this tube, the greater will be the force required to push the piston down, for the resistance to be overcome is the pressure due to the column of water raised.

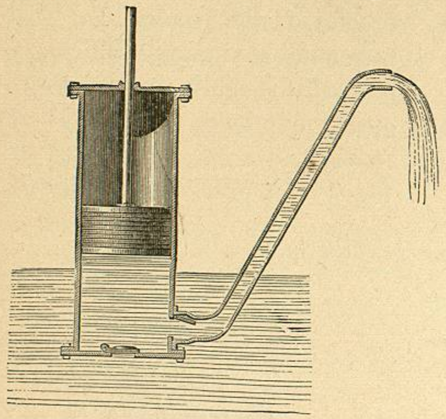

Fig. 158.—Forcing-pump.

The forcing-pump most frequently has a short suction-pipe leading from the reservoir, as represented in Fig. 159. In this case the water is raised from the reservoir into the barrel by atmospheric pressure during the up-stroke, and is forced from the barrel into the ascending pipe in the down-stroke.

259. Plunger.—When the height to which the water is to be forced is very considerable, the different parts of the pump must be very strongly made and fitted together, in order to resist the enormous pressure produced by the column of water, and to prevent leakage. In this case the ordinary piston stuffed with tow or leather washers cannot be used, but is replaced by a solid cylinder of metal called a *plunger*. Fig. 160 represents a section of a pump thus constructed. The plunger is of smaller section than the barrel, and passes through a stuffing-box in which it fits air-tight. The volume of water which enters the barrel at each up-stroke, and is expelled in the down-stroke, is the same as the volume of a length of the plunger equal

to the length of stroke; and the hydrostatic pressure to be overcome is proportional to the section of the plunger, not to that of the barrel. As the operation proceeds, air is set free from the water, and would eventually impede the working of the pump were it not permitted to escape. For this purpose the plunger is pierced with a narrow passage, which is opened from time to time to blow out the air.

The drainage of deep mines is usually effected by a series of pumps. The water is first raised by one pump to a reservoir, into which dips the suction-tube of a second pump, which sends the water up to a second reservoir, and so on. The piston-rods of the different pumps are all joined to a single rod called the *spear*, which receives its motion from a steam-engine.

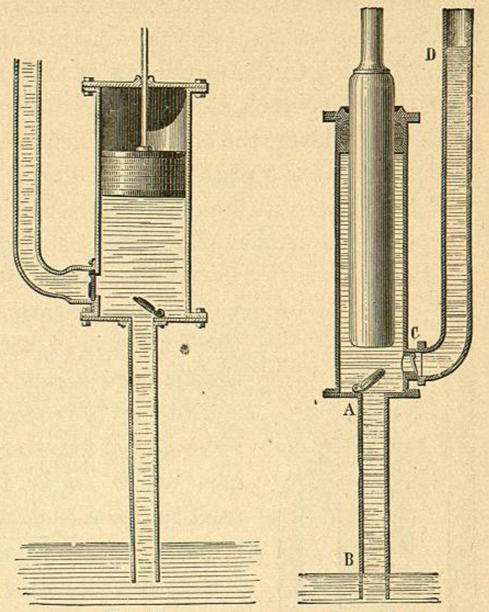

Fig. 159. Fig. 160.
Suction and Force Pump.

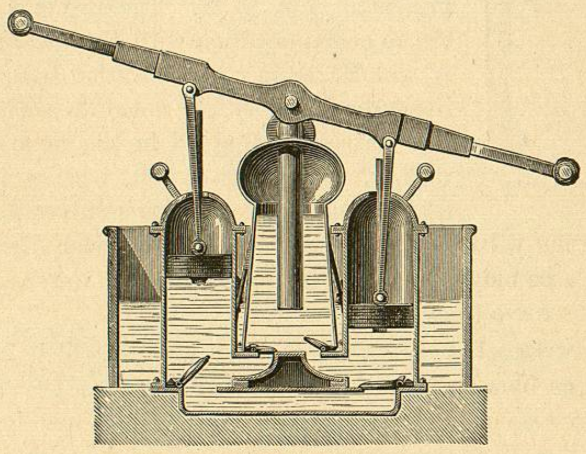

Fig. 161.—Fire-engine.

260. Fire-engine.—The ordinary fire-engine is formed by the union of two forcing-pumps which play into a common reservoir, containing in its upper portion (called the air-chamber) air compressed by the working of the engine. A tube dips into the water in this reservoir, and to the upper end of this tube is screwed the leather hose through which the water is discharged. The piston-rods are jointed to a lever, the ends of which are raised and depressed alternately, so that one piston is ascending while the other is descending. Water is thus continually being forced into the common reservoir except at the instant of reversing stroke, and as the compressed air in the air-chamber performs the part of a reservoir of work (nearly analogous to the fly-wheel), the discharge of water from the nozzle of the hose is very steady.

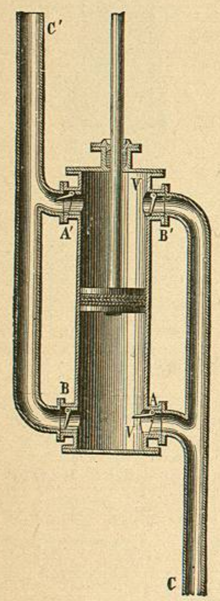

Fig. 162.
Double-action Pump.

The engine is sometimes supplied with water by means of an attached cistern (as in Fig. 162) into which water is poured; but it is more usually furnished with a suction-pipe which renders it self-feeding.

261. Double-acting Pumps.—These pumps, the invention of which is due to Delahire, are often employed for household purposes. They consist of a pump-barrel VV (Fig. 162), with four openings in it, A, A′, B, B′. The openings A and B′ are in communication with the suction-tube C; A′ and B are in communication with the ejection-tube C′. The four openings are fitted with four valves opening all in the same direction, that is, from right to left, whence it follows that A and B′ act as suction-valves, and A′ and B as ejection-valves, and, consequently, in whichever direction the piston may be moving, the suction and ejection of water are taking place at the same time.

262. Centrifugal Pumps.—Centrifugal pumps, which have long been used as blowers for air, and have recently come into extensive use for purposes of drainage and irrigation, consist mainly of a flat casing or box of approximately circular outline, in which the fluid is made to revolve by a rotating propeller furnished with fans or blades. These extend from near the centre outwards to the circumference of the propeller, and are usually curved backwards. The

fluid between them, in virtue of the centrifugal force generated by its rotation, tends to move outwards, and is allowed to pass off through a large conduit which leaves the case tangentially.

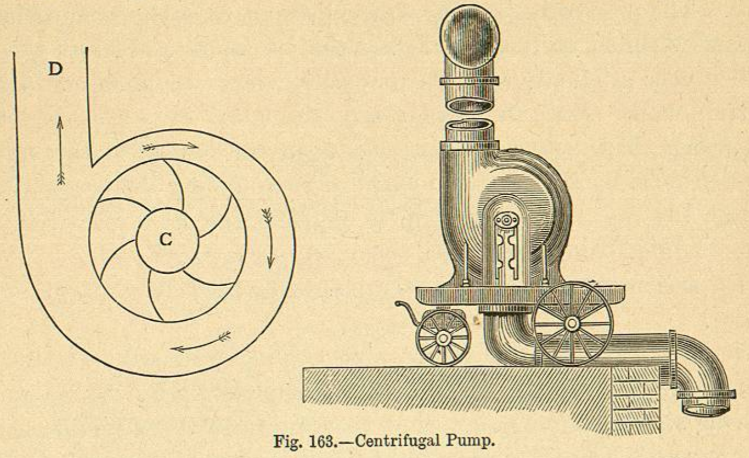

Fig. 163.—Centrifugal Pump.

The first part of Fig. 163 is a section of the propeller and casing, C being a central opening at which the fluid enters, and D the conduit through which it escapes. The second part of the figure represents a small pump as mounted for use. The largest class of

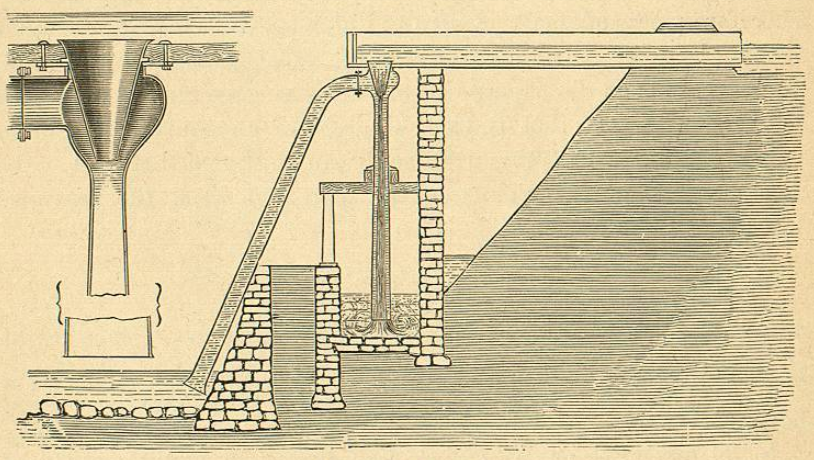
Fig. 164.—Jet Pump.

centrifugal pumps are usually immersed in the water to be pumped, and revolve horizontally.

263. Jet-pump.—The jet-pump is a contrivance by Professor

James Thomson for raising water by means of the descent of other water from above, the common outfall being at an intermediate level. Its action somewhat resembles that of the blast-pipe of the locomotive. The pipe corresponding to the locomotive chimney must have a narrow throat at the place where the jet enters, and must thence widen very gradually towards its outlet, which is immersed in the outfall water so as to prevent any admission of air during the pumping. The water is drawn up from the low level through a suction-pipe, terminating in a chamber surrounding the jet-nozzle.

Fig. 164 represents the pump in position, the jet-nozzle with its surroundings being also shown separately on a larger scale.

The action of the jet-pump is explained by the following considerations.

Suppose we have a horizontal pipe varying gradually in sectional area from one point to another, and completely filled by a liquid flowing steadily through it. Since the same quantity of liquid passes all cross-sections of the pipe, the velocity will vary inversely as the sectional area. Those portions of the liquid which are passing at any moment from the larger to the smaller parts of the pipe are being accelerated, and are therefore more strongly pushed behind than in front; while the opposite is the case with those which are passing from smaller to larger. Places of large sectional area are therefore places of small velocity and high pressure, and on the other hand, places of small area have high velocity and low pressure. Pressure, in such discussions as this, is most conveniently expressed by *pressure-height*, that is, by the height of an equivalent column of the liquid. Neglecting friction, it can be shown that if v_1, v_2 be the velocities at two points in the pipe, and h_1, h_2 the pressure-heights at these points,

$$v_2^2 - v_1^2 = 2g\,(h_1 - h_2),$$

g denoting the intensity of gravity. The change in pressure-height is therefore equal and opposite to the change in $\frac{v^2}{2g}$. This is for a horizontal pipe.

In an ascending or descending pipe, there is a further change of pressure-height, equal and opposite to the change of actual height.

Let H be the pressure-height at the free surfaces, that is, the height of a column of water which would balance atmospheric pressure;

k the difference of level between the jet-nozzle and the free surface above it.

l the difference of level between the jet-nozzle and the free surface of the water which is to be raised.

v the velocity with which the liquid rushes through the jet-nozzle,

then the pressure-height at the jet-nozzle may be taken as $H + k - \frac{v^2}{2g}$; and if this be less than $H - l$ the water will be sucked up. The condition of working is therefore that

$$H - l \text{ be greater than } H + k - \frac{v^2}{2g}, \text{ or}$$

$$\frac{v^2}{2g} \text{ greater than } k + l,$$

where it will be observed that $k + l$ is the difference of levels of the highest and lowest free surfaces.

264. Hydraulic Press.—The hydraulic press (Fig. 165) consists of a suction and force pump *aa* worked by means of a lever turning about an axis O. The water drawn from the reservoir BB is forced along

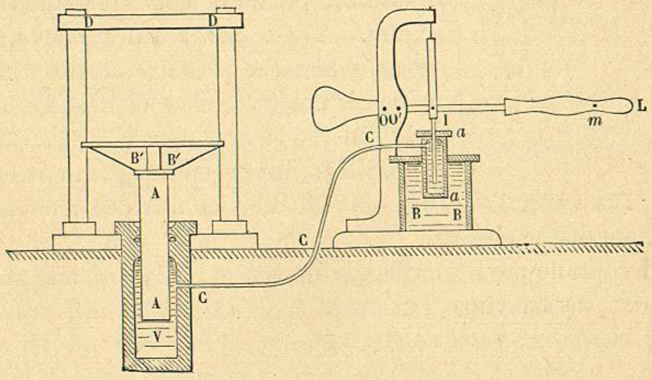

Fig. 165.—Bramah Press.

the tube CC into the cistern V. In the top of the cistern is an opening through which moves a heavy metal plunger AA. This carries on its upper end a large plate B′B′, upon which are placed the objects to be pressed. Suppose the plunger A to be in its lowest position when the pump begins to work. The cistern first begins to fill with water; then the pressure exerted by the plunger of the pump is transmitted, according to the principles laid down in § 141, to the bottom of the plunger A; which accordingly rises, and the objects to be pressed, being intercepted between the plate and the top of a fixed frame, are subjected to the transmitted pressure. The amount of this pressure depends both on the ratio of the sections of the pistons, and on the length of the lever used to work the force-pump. Suppose, for instance, that the distance of the point *m*, where the hand is applied, from the point O, is equal to twelve times the distance IO, and suppose the force exerted to be equal to fifty pounds. By the principle of the lever this is equivalent to a force of 50×12 at the point I; and if the section of the piston A be at the same time 100 times that of the piston of the pump, the pressure transmitted to A will be $50 \times 12 \times 100 = 60{,}000$ pounds. These are the ordinary conditions of the press usually employed in workshops. By drawing out the pin which serves as an axis at O, and introducing it at O′, we can increase the mechanical advantage of the lever.

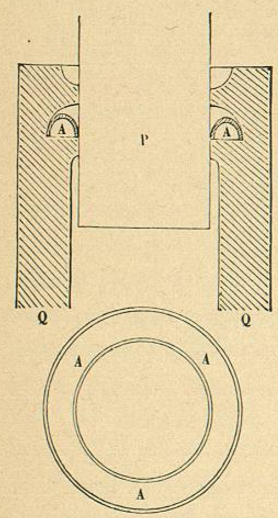

Fig. 166.—Cup-leather.

Two parts essential to the working of the hydraulic press are not represented in the figure. These are a safety-valve, which opens when the pressure attains the limit which is not to be exceeded; and, secondly, a tap in the tube C, which is opened when we wish to put an end to the action of the press. The water then runs off, and the piston A descends again to the bottom of the cistern.

The hydraulic press was clearly described by Pascal, and at a still earlier date by Stevinus, but for a long time remained practically useless; because as soon as the pressure began to be at all strong, the water escaped at the surface of the piston A. Bramah invented the *cupped leather collar*, which prevents the liquid from escaping, and thus enables us to utilize all the power of the machine. It consists of a leather ring AA (Fig. 166), bent so as to have a semicircular section. This is fitted into a hollow in the interior of the sides of the cistern, so that water passing between the piston and cylinder will fill the concavity of the cupped leather collar, and by pressing on it will produce a packing which fits more tightly as the pressure on the piston increases.

The hydraulic press is very extensively employed in the arts.

It is of great power, and may be constructed to give pressures of two or three hundred tons. It is the instrument generally employed in cases where very great force is required, as in testing anchors or raising very heavy weights. It was used for raising the sections of the Britannia tubular bridge, and for launching the *Great Eastern*.