CHAPTER 16

PUMPS AND PUMPING

ART. 192. GENERAL NOTES AND PRINCIPLES

Among the simple devices for raising water that have been used for many centuries, and which may be called lift pumps in a general way, are the sweep and windlass, buckets attached to a revolving wheel, the chain and bucket pump where the buckets move in a cylinder, and the Archimedian screw. The chain and bucket pump was probably first used by the Chinese in the form of an inclined trough in which moved the buckets attached to the endless chain, and this device in various forms has been used in all countries for lifting water from wells. The Archimedian screw, invented by the great engineer Archimedes when he was in Egypt, about 240 B.C., consists of a tube wound spirally around an inclined cylinder. When the lower end is placed under water and the cylinder revolved, the water is lifted and flows out of the upper end of the tube. This screw pump is still in use in northern Egypt, and it is said to be a satisfactory apparatus for a low lift.

The fact that water would sometimes rise into a space from which the air had been removed was known at a remote antiquity, and this was frequently explained by the statement that "nature abhors a vacuum." It was not until the middle of the seventeenth century that the true reason of this phenomenon was explained through the researches of Torricelli and Pascal (Art. 4), but prior to this time a rude form of suction pump, made by attaching a pipe to a bellows at the opening where the air usually enters, was used in both France and Germany. In 1732 the first true suction and lift pump was devised by Boulogne, and a little later the suction and force pump came into use.

The force pump is a device for raising water by means of pressure exerted on it by a piston. The syringe, which has been known from very early times, is an example of this principle, but the first true force pump was invented in Egypt about 250 B.C., by Ctesibius, a Greek hydraulician, and the description of it given by Vitruvius indicates that it was used to some extent by the Romans. The early force pumps were placed with their cylinders below the level of the water to be lifted, and had valves which closed under the back pressure of the water. By placing the cylinders above the water level and utilizing the principle of suction, the suction and force pump originated.

All devices for raising water may be classified under the three principles above mentioned: that of lifting in buckets, drawing it up by suction, or forcing it up by pressure, or under combinations of these. The lift or bucket principle is mainly employed for small quantities of water and has only a limited use in engineering practice. The suction principle, combined with lift or pressure, is extensively used, but in no event can the height of the suction exceed 34 feet, for it is the atmospheric pressure that causes the water to rise when the air above it is exhausted; under this principle also may be put injector pumps which operate under the action of negative pressure-head (Art. 31). The principle of direct pressure governs not only the force pump, but rotary and centrifugal pumps and also the devices for raising water by compressed air.

Whenever water is raised from a lower to a higher level, an amount of work must be expended greater than the theoretic work required to lift the given weight of water through the given height. The excess, called the lost work, is spent in overcoming resistances of friction and inertia. In designing pumps it is the object to reduce these losses to a minimum, so that the greatest economy in operation may result. The subject will here be mainly considered from a hydraulic standpoint, the object being to set forth the fundamental principles by which hydraulic losses may be avoided as far as possible.

Let W be the weight of water raised per second and h the height of the lift, then the useful work per second k is Wh. Let the total work expended per second be called K, then the efficiency of the apparatus is $e = k/K$. The work K to be considered here is that delivered to the pump and does not include that lost in transmission from the motor, since this, of course, is not fairly chargeable against the pump or lifting apparatus. If K be replaced by $W(h + h')$, where h' is the head lost in overcoming the frictional resistances, then the efficiency may be written

$$e = \frac{k}{K} = \frac{h}{h + h'} \qquad (192)$$

which is less than unity, since h' cannot be made zero.

The power required to operate a pump to raise the weight W of water per second through the height h is easily computed if the efficiency of the pump is known. For example, to raise 150 gallons per second through a height of 20 feet with a pump having an efficiency of 62 percent, the work which must be imparted to the pump per second is

$$K = k/e = (150 \times 8.335 \times 20)/0.62 = 40\,340 \text{ foot-pounds,}$$

and this, divided by 550, gives 73.3 horse-powers.

Prob. 192. A pump raises 20.5 cubic feet of water per second through a height of 127.5 feet. The lost head in the pump and pipes amounts to 13.5 feet. Compute the efficiency of the pumping plant and the power required to operate it.

Art. 193. Raising Water by Suction

The term "suction" is a misleading one unless it be clearly kept in mind that water will not rise in a vacuum tube unless the atmospheric pressure can act underneath it. For example, no amount of rarefaction above the surface of the water in a glass bottle will cause that water to rise. When the tube is inserted into a river or pond, however, the water will rise in it when a partial vacuum is formed, since the atmospheric pressure which is transmitted through the water pushes it up until equilibrium is secured (Art. 4). The mean atmospheric pressure of 14.7 pounds per square inch at the sea level is equivalent to a height

of water of 34 feet, and this is the limit of raising water by suction alone. In practice this height cannot be reached on account of the impossibility of producing a perfect vacuum, and it is found that about 28 feet is the maximum height of suction lift.

The height of the water barometer varies with the state of the weather, with the elevation above sea level, and with the temperature. The value of 34 feet is that corresponding to a reading of 30 inches on the mercury barometer at a temperature of 32° Fahrenheit. For higher temperatures more or less vapor is evaporated from the water surface and fills the suction tube, so that a complete vacuum cannot be formed. When the mercury barometer reads 30 inches, the water barometer is only 33.4 feet if the temperature of the water is 60° Fahrenheit, 32.4 feet at 90°, about 30 feet for 120°, about 23 feet for 160°, about 6 feet for 200°, and for 212° its height is zero, since the tube is then filled with steam. Hence water at the boiling-point cannot be raised by suction.

Fig. 193 gives two diagrams illustrating the principle of action of the common suction and lift pump. It consists of two vertical tubes BD and BE, the former being called the suction pipe and the latter the pump cylinder. The piston A in the pump cylinder has a valve opening upward, and the valve B at the top of the suction pipe also opens upward. In the left-hand diagram the piston is descending, the valve A being open and B being closed under the pressure of the air in the space between them. In the right-hand diagram the piston is

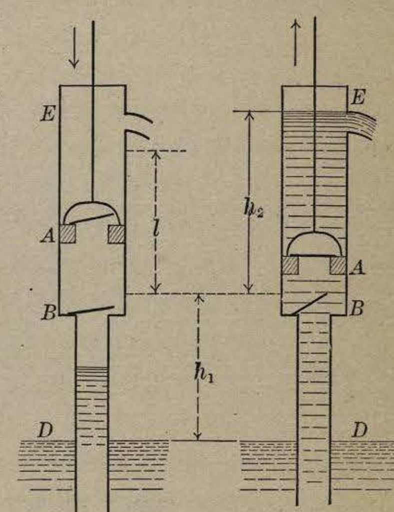

Fig. 193.

ascending, the valve A being closed by the pressure of the air or water above it, while B is open, owing to the excess of atmospheric pressure in BD above that in AB. In the first diagram the piston has made only one or two strokes, so that the water has risen but a short distance in the suction pipe. In the second diagram the piston has made a sufficient number of strokes so that the pump cylinder is full of water which is flowing out at the spout E.

Let h_1 be the distance from the water level D to the lowest position of the piston; this is called the height of lift by suction. Let h_2 be the height from the lowest position of the piston to the spout where the water flows out; this is called the height of lift by the piston. The distance $h_1 + h_2$ is the vertical height through which the water is raised, and if W be the weight of water raised in one second, the useful work per second is $W(h_1 + h_2)$. The energy imparted to the pump through the piston rod is always greater than this useful work, since energy is required to overcome the frictional resistances due to the motion of the water and piston, as also to overcome the resistance of inertia in putting them into motion.

To discuss the action of the pump in detail, let l be the stroke of the piston, that is, the distance between its highest and lowest positions. Let A be the area of the cross-section of the pump cylinder and a that of the suction pipe. Let the piston be supposed to be at its lowest position at the beginning of the operation when no water has been raised in the suction pipe above the level D in Fig. 193. On raising the piston through the stroke l it describes the volume Al, and the volume of air ah_1 now has the volume $Al + a(h_1 - x)$ in which x is the height through which the water rises during the upward stroke. Let h_a be the height of a water barometer corresponding to the air pressure above the water level at the beginning of the stroke, then $h_a - y$ is the pressure-head at the end of the stroke. Since, by Mariotte's law, the pressure of a given quantity of air is inversely as its volume, $(h_a - x)/h_a$ equals $ah_1/(Al + ah_1 - ax)$, whence,

$$x^2 - (rl + h_1 + h_a)x + rlh_a = 0$$

in which r represents the ratio A/a. For example, let A be 8 and a be 2 square inches, or $r = 4$, let h_1 be 20 and l be 1.5 feet;

then for $h_a = 34$ feet, the water rises during the first upward stroke to the height $x = 3.6$ feet. For the second upward stroke h_a is $34.0 - 3.6 = 30.4$ feet and h_1 is $20.0 - 3.6 = 16.4$ feet; then the formula gives $x = 3.7$ feet, so that the water level now stands 7.3 feet above its original level D. Proceeding in like manner, it is found that at the end of the third upward stroke the water stands at 11.2 feet above its original level. Similarly at the end of the fourth upward stroke it is found to be 15.3 feet above D, while at the end of the fifth upward stroke it has reached a height of 19.8 feet above its original level. During the progress of the sixth upward stroke the water enters the pump cylinder, during the next downward stroke it flows through the piston valve, and in the seventh upward stroke the water above the piston is lifted and flows out through the spout.

The preceding discussion supposes that there is no leakage of air through and around the piston, but this cannot be attained in practice; hence the degree of rarefaction below the piston is never so great as the above formula gives, and the number of strokes required to elevate the water above the valve B is larger than the computed number. When the suction height is greater than 25 feet, it becomes difficult to secure sufficient rarefaction to lift the water, and hence a foot valve, also opening upward, is placed in the suction pipe below the water level D. The pump cylinder and suction pipe can then be primed, or filled with water from above, and after this is done there will be no difficulty in operating the pump. If there is no foot valve, it will be necessary to have a very long piston stroke in order to start the pump, but with a foot valve the stroke of the piston may be any convenient length.

The action of this pump is intermittent, and water flows from the spout only during the upward stroke of the piston. When there are N upward strokes per minute, the discharge in one minute is NAl, if the piston and its valve be tight. The useful work per minute is $NwAl(h_1+h_2)$, if w be the weight of a cubic unit of water. When l and h_1+h_2 are in feet, A in square feet, and w in pounds per cubic foot, the horse-power expended in this useful work is

$$\overline{HP} = NwAl(h_1+h_2)/33\,000$$

and to this must be added the horse-power required to overcome the resistances of friction and inertia. This additional power often amounts to as much as that needed for the useful work, and in this case the efficiency of the pump is 50 percent. Suction and lift pumps are of numerous styles and sizes, the simplest being of square wooden tubes or of round tin-plate tubes with leather valves, and these can be readily made by a carpenter or tinsmith. They are mainly used for small quantities of water and for temporary purposes.

Prob. 193. The diameter of the pump cylinder is 8 inches and that of the suction pipe is 6 inches, while the vertical distance from the water level to the spout is 23 feet. If the pump piston makes 30 upward strokes per minute, each 9 inches long, what horse-power is required to operate the pump if its efficiency is 45 percent?

Art. 194. The Force Pump

A force pump is one that has a solid piston which can transmit to the water the pressure exerted by the piston rod and thus cause it to rise in a pipe. The early force pumps had little or no suction lift, as the pump cylinder was immersed in the body of water which furnished the supply, but the modern forms usually operate both by suction and pressure, the former occurring in a suction pipe and the latter in the pump cylinder. Fig. 194*a* shows the principle of action of the common vertical single-acting suction and force pump in which there is no water above the piston. In the left-hand diagram the piston is ascending, and the water is rising in the suction pipe BD under the upward atmospheric pressure; this ascent of the water occurs in exactly the same manner as explained in Art. 193, and after several strokes its level rises above the suction valve B. The right-hand diagram shows the piston descending and forcing the water up the discharge pipe CE. At C, where this pipe

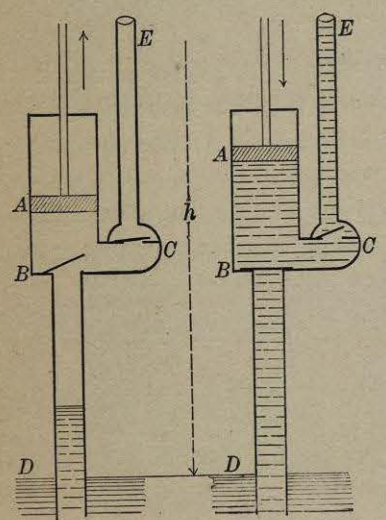

Fig. 194*a*.

joins the pump cylinder, is a check valve which closes on the upward stroke and thus prevents the water in CE from returning into the pump cylinder, while it opens on the downward stroke under the upward pressure of the water.

Let A be the area of the cross-section of the pump cylinder and l the length of the stroke of the piston. Then at each upward stroke a volume of water equal to Al is raised through the suction pipe, and in each downward stroke the same volume is raised in the discharge pipe. If h be the total lift above the water level D and w the weight of a cubic unit of water, the work done in each double stroke is $wAlh$. If there be made N double strokes per minute, the useful work per minute is $NwAlh$. When all dimensions are in feet, the horse-power required to do this useful work is found by dividing this quantity by 33 000, and the actual horse-power required to run the pump is greater than this by the amount needed to overcome the frictional resistances. This additional power will depend upon the length of the suction and discharge pipes, the speed at which the pump is operated, the friction along the sides of the piston, the losses of head in the passage of the water through the valve openings, and the losses of energy due to putting the water into motion at each stroke. The efficiency of single-acting suction and lift pumps hence varies between wide limits, 90 percent or more being obtained only for very low speeds and lifts, while for high speeds and lifts it may be 20 percent or less.

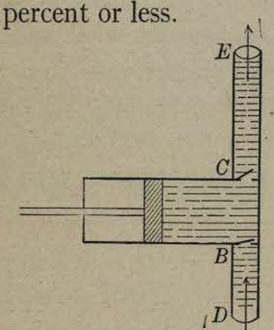

Fig. 194*b*.

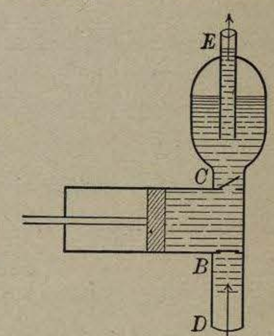

Fig. 194*c*.

The cylinder of the single-acting pump may be placed horizontal, as seen in Fig. 194*b*, where BD is the suction pipe and

CE the discharge pipe. When the piston moves toward the left, the suction valve B opens and the check valve C closes; when it moves toward the right, B closes and C opens. The discharge is intermittent, as in the previous case, but the horizontal position of the piston sometimes renders the connection of the piston rod to the motor more convenient. If the height of the suction lift be equal to that of the discharge lift, the force required to move the piston will be the same in each stroke and the pump will work with less shock than where the two lifts are unequal. Usually, however, the height of the discharge lift is greater than that of the suction lift, and the force required to move the piston is then the greatest when it moves from left to right in Fig. 194*b*. In order to equalize the forces exerted by the motor the duplex pump was devised; this consists of two single-acting cylinders placed side by side and connected to the same suction and discharge pipe, the pistons moving so that one exerts suction while the other is forcing the water upward. Three single-acting cylinders are also sometimes connected with the same suction and discharge pipe, in which case it is called the triplex pump. Duplex and triplex pumps give a more nearly continuous flow of water in both the suction and discharge pipes, and thus diminish the shocks that occur in a pump with one cylinder, while the efficiency is materially increased because the losses due to starting and stopping the columns of water are in large part avoided.

A double-acting pump is one having a single cylinder in which a solid piston or plunger exerts suction and pressure in both strokes and thus gives a nearly continuous flow through suction and discharge pipes. Fig. 194*d* shows the form known as the piston pump, while Fig. 194*e* is that called the plunger pump, the piston being replaced by a long cylinder moving in a short stuffing box AA. In both figures D is the suction pipe and E the discharge pipe. When the piston moves from left to right, the valves B_1 and C_2 open, while B_2 and C_1 close; when it moves in the opposite direction, B_2 and C_1 open, while B_1 and C_2 close. The plunger pump was invented in the seventeenth century, and its advantages over the piston type are so great that it is now

extensively used for large pumping machinery. The cylinder of the piston pump must be bored to an exact and uniform size, and its piston must be carefully packed, while in the plunger pump only the short length of the stuffing box is bored and packed, the

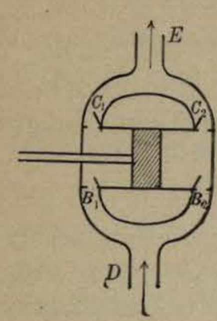

Fig. 194*d*.

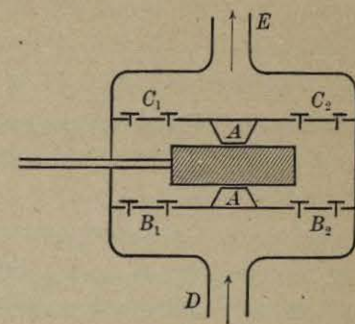

Fig. 194*e*.

plunger itself having no packing. The water lifted in one stroke of either pump is Al, where A is the area of the piston and l the length of its stroke, provided there is no leakage past the packing.

For all these forms of pumps a foot valve should be placed in the suction pipe, if the suction lift exceeds 20 feet, in order that the pump may be readily primed (Art. 193). To reduce the shocks that occur to a certain extent even in the double-acting pumps, an air chamber is frequently attached to the discharge pipe so that the confined air may distribute and lessen the shock that would otherwise be concentrated on the end of the discharge pipe. Fig. 194*c* shows such an air chamber attached to a single-acting pump; in the upper part of it is seen the compressed air which is receiving the pressure from the piston. After the check valve C closes the pressure of this air maintains the flow up the discharge pipe E, and hence the air chamber helps to avoid the losses due to intermittent flow. A duplex pump or a double-acting pump, when provided with an air chamber of proper size, will work very smoothly.

Prob. 194. Consult Ewbanks' Hydraulics and Mechanics (New York, 1847), and describe a method of raising water through a low lift by means of a frictionless plunger pump. Ewbank notes that a stout young man weighing 134 pounds raised $8\frac{1}{3}$ cubic feet per minute with this machine to a height of $11\frac{1}{2}$ feet, and worked at this rate nine hours per day. If the efficiency of this pump was unity, what horse-power did the stout young man exert? Was his performance high or low?

Art. 195. Losses in the Force Pump

A reliable numerical computation of the hydraulic losses of energy in the force pump cannot be made without knowing the constants to use in finding the losses of head due to the valves (Art. 92), and these have been experimentally determined for only a few special forms. The valves shown in most of the figures of the preceding articles are simple flap valves, but poppet valves are more generally used, and Fig. 194*e* indicates such. In passing through a valve the water loses energy in friction, and also in impact due to the subsequent expansion. Since pumps are made in numerous forms having different details, general discussions of losses are difficult to make. The attempt will, however, be undertaken for the plunger force pump of Fig. 194*e*. Let h be the total height through which the water is lifted by both suction and pressure, and h' be the sum of all the hydraulic losses of head. Let K be the energy delivered per second to the piston rod, k' the energy expended in friction in the stuffing boxes of the piston rod and plunger, q the discharge per second, and w the weight of a cubic unit of water. Then

$$K = k' + wq\left(h + \frac{v_2^2}{2g} + h'\right)$$

and the pump should be so arranged as to make the losses k' and h' as small as possible. Only the hydraulic losses will be considered in the following discussion.

By means of the principles of Chap. 7 a rough formulation of the elements that make up the lost head h' can be effected, supposing the flow in the pipes to be steady. Let l_1 be the length, d_1 the diameter, and v_1 the velocity for the suction pipe, and l_2, d_2, and v_2 the same things for the discharge pipes. Let $2n$ be the number of valves in the suction and discharge chambers (Fig. 194*e*), all being taken of the same size, and let V denote the velocity of the water through each valve opening. Let these chambers be so large that the velocity of the water through them is very small compared to that in the pipes and valve openings. Then

$$h' = \left(m + f\frac{l_1}{d_1} + 1\right)\frac{v_1^2}{2g} + 2(m' + 1)\frac{V^2}{2g} + f_2\frac{l_2}{d_2}\frac{v_2^2}{2g} \qquad (195)$$

gives all the hydraulic losses of head. In the first parenthesis m indicates the loss due to entrance at the foot of the suction pipe (Art. 89), fl_1/d_1 the friction loss in the suction pipe (Art. 90), and 1 the loss due to expansion (Art. 76) as the water enters the suction chamber B_1B_2. In the second parenthesis m' indicates the loss due to the open valves (Art. 92) and 1 that due to sudden expansion as the water enters the pump cylinder through the suction valves and the discharge chamber C_1C_2 through the discharge valves. The last term gives the loss due to friction in the discharge pipe. If there is an air chamber on the discharge pipe, another term might be introduced, but as the effect of the air chamber in reducing water hammer is a beneficial one, this term need not be used. The starting and stopping of the piston brings in other losses of energy, but as these are not hydraulic losses they will not be considered here.

When the pipes are long, the losses due to pipe friction will far exceed those in the pump, and are not fairly chargeable against it as a machine; hence in order to consider the pump alone the lengths l_1 and l_2 may be made equal to zero, as also m in the first parenthesis. Then formula (195) becomes

$$h' = \frac{v_1^2}{2g} + 2(m' + 1)\frac{V^2}{2g}$$

in which the first term of the second member gives the loss of head in entering the suction chamber, and the second those occurring in entering and leaving the pump cylinder. This equation appears, at first thought, to indicate that a suction chamber is not a hydraulic advantage, although it is known to afford a practical advantage in causing the valves to operate successfully, as also in permitting ready access to them. If a be the area of each valve opening, and a_1 that of the suction pipe, then a_1v_1 must equal $\frac{1}{2}naV$, since the same quantity of water passes per second through the suction pipe and through $\frac{1}{2}n$ valves. Accordingly the total loss of head in the pump may be written

$$h' = \frac{v_1^2}{2g} + 8(m' + 1)\left(\frac{a_1}{na}\right)^2\frac{v_1^2}{2g}$$