CHAPTER X.

ANALYSIS OF CHAMBER-WHEEL TRAINS.

§ 93.

Chaining of Spur-Gearing with Pressure-Organs.

THE constrained motion of a pressure-organ, rendered possible by enclosure in chamber-gear, is not limited to the circle of crank mechanisms,—where we have already traced the development of the principle,—but can be obtained in other trains, and has met with frequent applications in them. There are many trains, of various kinds, in which a pressure-organ may be substituted for a rigid link. The method of chambering already described requires again to be carried out, and under certain circumstances gives us very valuable results, and machines really suited for practical use. One interesting series of such inventions, which indeed were not arrived at by our analytical method, but which may none the less be considered under it, is furnished us by machines formed upon the chain $(R_z C_2)$. I proved some time since the mutual relationship—previously unknown—of a number of these machines.* We shall give them the common name of chamber-wheel trains or gear.

* *Berliner Verhandlungen*, 1868, p. 42. I published this investigation on chamber-wheel gear before I was able to avail myself of the kinematic notation. In comparing

A chamber-wheel train consists of a chain $(R_2 C_2)$ so formed into a mechanism, by making one of its links a chamber, that it can be chained with a pressure-organ which shall enter the spaces between the teeth, pair with them, move forward with them, and finally be compelled to leave them where the two wheels gear with each other. One or both of the spur-wheels is used as the piston, while the frame $C \ldots\ldots C$ is formed into the chamber. There are necessarily a number of solutions of this general problem. The machines thus obtained may—as we have already found in the case of the crank mechanisms—be used either to cause the motion of a pressure-organ (as in a pump), or as a "prime mover," receiving motion from the pressure-organ, or for other purposes. The general character of the mechanism remains always the same, the special arrangement of it adopted depending upon the particular object in view. We shall here briefly examine a few of the most important forms of chamber-wheel gear.

§ 94.

The Pappenheim Chamber-wheels.

Plate XXXII.

The spur-wheel mechanism $(C_z C_2'')^c$ (Fig. 278), as the geometrically simplest case of $(R_z C_2)$, furnishes our first chamber-wheel train; the form chosen for it being that in which the wheels *a* and *b* are made equally large. The frame *c* becomes a chamber encircling *a* and *b*, and furnished with an inlet and outlet passage upon opposite sides of the two shafts. This gives us the oldest form of chamber-wheel gear, the construction of which is shown schematically in Figs. 1 and 2, Pl. XXXII. Two similar spur-wheels, *a* and *b*, having their teeth made so as to work without play, are enclosed in a chamber which has two semi-cylindrical wings, with which the points of the teeth remain in contact during their motion. The chamber has two openings, one on each side of the parallel shafts, and has plane end surfaces with which the ends of the

it with the present chapters it will be noticed that the general method and scope of both are very much alike, although here I can go considerably further into the matter than was formerly possible.—*R.*

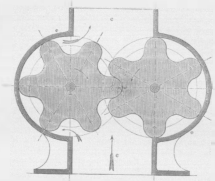


Fig. 1.—Pappenheim.
$(C_z\, C_2'')^c\,;\ (V\!\pm) = ab,\, c.$

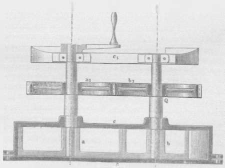


Fig. 2.

wheels must remain in close contact. The shafts of the wheels pass bey ond the chamber, and are kinematically connected by two equal spur-wheels, a_1 and b_1. If now one of the axes—that of a, for instance—be caused to revolve, the other will turn with equal angular velocity in the opposite direction. If the turning take place in the direction of the arrows in Fig. 1, and the lower opening be connected with a reservoir of water, then as the wheels revolve the spaces between their teeth will be filled with water, which they will transfer from one side of the chamber to the other. On account of the contact between the teeth where they gear together at $m\,n$ no water can pass backwards, so that it must be driven onwards through the delivery-pipe. The machine may therefore serve as a pump, and for this purpose offers the advantages that it has neither valves nor any motions but rotary ones.

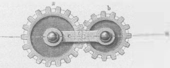


FIG. 278.

There is no difficulty in so forming the teeth of a and b that their profiles are always in contact in at least one point somewhere in the neighbourhood of $m\,n$, and that the point of contact passes continuously through the whole profiles as they move. Under the supposition that this is the case—as it is in Fig. 1—no water can pass back from the upper to the lower part of the chamber between a and b. The amount of water passing through the machine is then directly proportional to the number of revolutions of the wheels. If these move uniformly, the water is delivered in a continuous stream, on which account the machine might be well suited for a fire-pump.

The volume of water delivered by the pump per revolution is equal to the contents of the spaces * of both wheels, or as the volume of the teeth may in this case be considered the same as the volume of the spaces, is approximately equal to the contents of a

* A "space" is the volume enclosed between the sides of two consecutive teeth, and limited above and below by the point and root cylinder of the teeth.

cylindric ring whose inner and outer radii are those of the bottom and top of the teeth respectively, the annular space, that is, between the point and root cylinders. This we may call shortly the tooth-ring.

If, therefore, it be desired to increase the amount of water delivered per revolution without changing the diameter of any part of the wheel, it is only necessary to lengthen *a* and *b* in the direction of their axes. If the head of water be not great, and the angular velocity of the wheels not too small, careful construction may so reduce the loss of water as to make it not worth considering. The arrangement, therefore, is one which in many cases may furnish a really useful water-pump.

As a pump, indeed, the machine is already very old. Weisbach calls it* Bramah's rotary pump, and says that Leclerc improved it (by placing packing wedges in the ends of the teeth); other writers ascribe it to Leclerc himself. This would take back the date of the invention to the end of the last century. But long before this, in 1724, the pump had been described as old by Leupold,† and called "Machina Pappenheimiana"; he headed it "A chamber apparatus with two moving wheels, called by D. Becher Machina Pappenheimiana." Now Becher's work‡ appeared in the first half of the 17th century. Besides this, however, Kircher, Schott,§ Leurechin, and also Schwenter, in his "Mathematischen Erquickstundenr" (A.D. 1636, p. 485), have described the same machine with the alteration that the wheels have four teeth instead of six, and that they do not name Pappenheim. The machine is now therefore over 230 years old; it was already known in the time of the Thirty Years' War, and all accounts agree in making it a German invention. Whether Pappenheim was the name of its inventor, or of his city only, remains uncertain; we are quite justified, however, in any case in calling it the Pappenheim pump. In France Grollier de Servières (1719) is often named as its inventor.‖ But this date is that only of the appearance of a description by the younger de Servières of the mechanical collection of his grandfather,

* Weisbach, *Mechanik*, iii., p. 843. † *Theatrum Mach. Hydraul.*, vol. i., p. 123.

‡ *Trifolium Becherianum*, which is unfortunately not to be found either in the Königl. Bibliothek in Berlin or in the Library of the British Museum.

§ Kasper Schott, *Mechanica Hydraulica Pneumatica*, Mainz, 1657. The wheels shown in a little copper-plate engraving have here nineteen teeth.

‖ *Propag. Industr.*, 1868, iii., p. 20.

in which moreover he does not mention the latter as the inventor of the machine.* The collection appears to have been founded about 1630.

I must here remark that the two external spur-wheels, *a* and *b*, are omitted both in Leupold's beautiful copper-plates and in the small woodcuts of Schwenter, as well as by Bramah and Leclerc. There is certainly no absolute necessity for their employment, for the pump-wheels may be used instead; but the oblique action of the latter when in the relative positions shown in Fig. 1 would soon damage the teeth. The use of the wheels *a* and *b* is therefore always to be recommended, and their existence will be assumed in the remaining chamber-wheel trains shown in our plate. We need not here enter into the delineation of the profiles of the wheel-teeth, which have been already mentioned in § 31. We may merely mention that in this case the points of the teeth are semi-circular (as in Leupold's engraving), and the profiles of their flanks are such as work with these curves,—they differ little from circular arcs.

The Pappenheim machine may be used for gaseous bodies as well as for liquids—for a blower, for example, or a gas-pump. Its action also may be reversed, so that the fluid drives the machine instead of being driven by it. The machine thus becomes a prime mover,—a chamber-wheel turbine, if water be the fluid used, or a rotary steam-engine if it be steam. Murdock, a contemporary of Watt,† attempted to apply it for the last-named purpose, using teeth with broader points, so that they could work against the chamber-walls, and fitting them also with packing pieces. The machine thus arranged could only be adapted for very light work, for the closure at the line of contact of the teeth, *m n*, would not suffice if a high pressure were used; Murdock's chamber-wheel steam-engine has therefore never found its way into practical use.‡

* Ewbank, *Hydraulic and other Machines*, Ed. of 1870, p. 285.

† Murdock was for many years an assistant of Watt, and became eventually (practically) a partner in the firm of Boulton and Watt. His engine, made in 1799, is described in Farey's *Treatise on the Steam Engine*, p. 676, and elsewhere.

‡ So far as regards economy in the quantity of steam used Dudgeon's rotary engine, which has been a good deal advertised during the last two or three years, is no doubt superior to Murdock's. In it a return is made to the use of wheels with numerous teeth (thirty-one in wheels twenty inches diameter), for which epicycloidal profiles are

The chamber-wheel gear can also be used in another way, viz., as a measuring instrument. It can, that is to say, if carefully constructed, serve as a water meter; for if a stream of water be allowed to pass through it, driving the wheels, the number of revolutions made by the latter gives the quantity of water passed in terms of the tooth-ring volume. We shall find further on other similar applications of chamber-wheel gear.

Still another application of the machine may be obtained by arranging it with a delivery-pipe of which the sectional area can be varied. By reducing this to a suitable extent the chamber-wheel train, working either with water or oil, forms a brake, which by the use of one or of two valves can be made either single or double acting. If the passages be suitably arranged the same quantity of fluid can be used over and over again; a brake of this kind, too, has no wearing parts, like those of an ordinary block-brake. Such a chamber-wheel brake, acting in the direction of rotation, and not preventing any other motion, may serve as a cataract, and be useful in those cases where it is wished to apply that apparatus in connection with rotary motions.

It will be seen that the chamber-wheel gear has a large range of applications. In its simplest form, without valves, it may be used as a pump (and is suitable for a fire-engine pump), as a steam-engine, or as a fluid meter; a trifling addition makes it available also as a brake or a cataract. It is well suited for working with (driving or being driven by) water or other liquids, and also viscous or merely plastic materials (so that it probably might be used as a clay or pug-mill), as well as for driving gaseous materials, as air

used. The steam is admitted at the side of the wheels into the space between two teeth, and the resulting motion takes place in the one or other direction according to whether the admission opening be placed a little above or below the line of centres. This makes both expansion and reversing possible. The only security against leakage, however, is the higher pairing between the surfaces of the teeth. At the sides of the wheels there is lower pairing, but no means are provided (or at least shown in the engraving) for taking up the wear which must occur there. Altogether I see no reason for supposing that this inventor will be more successful than his predecessors in inducing two bodies to rub upon each other under considerable pressure and at a great velocity without wear taking place, and all the consequences due to that inconvenient action.—See *Engineering*, Nov. 14, 1873. From some correspondence in subsequent numbers of the same journal it seems probable that the first to propose this use of steam from the centre outwards in a chamber-wheel-train was John Hackworth (*circa* 1840-45).

or coal-gas, if their pressure be small. It is indeed capable of a greater variety of useful applications than often exists for one and the same machine.

§ 95.

Fabry's Ventilator.

Plate XXXIII.

This well known machine is a chamber-wheel train used for a "wind pump" or ventilator. The Belgian engineer whose name it bears has introduced it with great success as a suction ventilator for mines, and is still occupied in improving it. Fig. 1 shows the profile of the wheels first used by Fabry.* The pump wheels *a* and *b* are here three-toothed, the profiles of the teeth at $m\,n$ and $m_1\,n_1$ being epicycloids upon the pitch circles, or their equidistants. At $o\,p$ the profiles touch on both sides of the centre line until m and n or m_1 and n_1 come together. The stream of air is therefore prevented from passing between the wheels, although the point of contact does not, as in the Pappenheim wheels, pass continuously through the whole profiles. The hollowing out of the teeth entails, however, the consequence that as each tooth leaves contact a small quantity of air is carried back to the suction-pipe. If we imagine the teeth to have been first arranged for continuous contact and then hollowed out, the capacity of the hollows thus made would give us exactly the quantity of air returned. The condition therefore remains, that the quantity of air delivered per revolution is very approximately equal in volume to the tooth-ring cylinder. Thus the hollowing of the teeth does not alter the quantity of air delivered; —it prevents, however, the complete uniformity of the delivery,—for the return of air takes place at intervals and not continuously. This want of uniformity might be a serious disadvantage if the machine were working with a considerable water-pressure, but for the purposes of a ventilator, especially where the velocity is small and the pressure low, it has little appreciable influence.

It is not necessary that the recesses in the chamber should be semi-cylindrical in order to insure the joint between them and the points of the teeth being kept for a sufficiently long time; it is

* Laboulaye, *Cinématique*, Second Edition, p. 793.

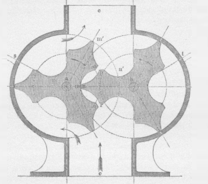


FIG. 1.—Fabry
$(C_z C_2'')^c$; $(V\pm) = ab, c.$

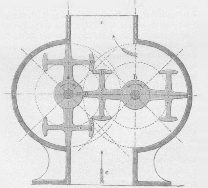


FIG. 2.—Fabry.
$(C_z\ C_2'')^c$; $(V\pm) = ab, c.$

sufficient if they subtend the pitch angle, or angle included between one pair of teeth. With such wheels as those of Fig. 1, for instance, they need not extend beyond *s* and *t*; while if they be made semi-cylindrical the wheels need have two teeth only. This form, as shown in Fig. 2, is that adopted in Fabry's later wheels. Epicycloidal profiles are again adopted for the faces *o p*, *q*, *r*, etc.; and at *m n* there is contact between the central arm of the wheel *b* and the root-cylinder or boss of *a*. The space between the latter and the cylindrical sides of the chamber is the tooth-ring cylinder, the volume of which again approximates very nearly to the volume of air delivered per revolution. Fabry's ventilators are constructed of from 3 to 4 metres diameter and 2 to 3 metres breadth, and move comparatively slowly, namely, at from 30 to 60 revolutions per minute.* The framework of the wheels is mostly made of wood, tin plates being nailed upon it at the places of contact *m n*, etc., so that the whole construction bears the least possible resemblance to a toothed wheel. We can therefore easily understand how the theoretic connection between the Pappenheim machine and that of Fabry has remained unnoticed by practical men.

§ 96.

Root's Blower.

Plate XXXIV.

The blowing machine of Root represented in Fig. 1, Pl. XXXIV. was exhibited at the Paris Exhibition of 1867.† The wheels were about three feet in diameter and nearly seven feet broad; they were driven at a great velocity, and delivered a large volume of air at a considerable pressure. The profile *p n r* is circular, and works continually in contact‡ with the profile *q m o* of the other wheel.

* Cf. *Zeitschrift des Vereins deutscher Ingenieure*, vol. i., p. 140;—Ponson, *Traité de l'Expl. des Mines de Houille; Polyt. Centralblatt*, 1858, p. 506; also *Civil-Ingénieur*.

† *The Engineer*, August, 1867, p. 146.

‡ I believe that now, at all events, the profiles of the wheels are made so as just not to come into contact; it is considered that the absence of friction thus attained more than compensates for the small leakage of air which occurs at ordinary pressures and velocities.

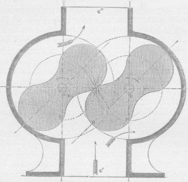


FIG. 1.—Jones, Root.
$(C_s C''_2)^c$; $(V\pm) = ab,c.$

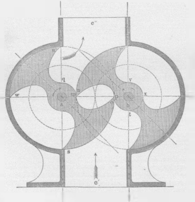


FIG. 2.—Root.
$(C_s C''_2)$; $(V\pm) = ab,c.$

It will be seen that the machine is a Pappenheim chamber-wheel train in which each wheel has two teeth. Root made the surfaces of the teeth at first of wood, afterwards of iron. His blower is constructed at various places, and is very extensively used; there were several at the Vienna Exhibition of 1873. Root does not appear, however, to have been the first inventor of this chamber-wheel train, for it was used as a gas-exhauster (made by George Jones of Birmingham) in 1859,* and does not appear to have been new even then.[53]

Fig. 2 is a section of a second form of Root's blower, in which the profiles of the teeth are altered. As in the chamber-wheel engine of Murdock already mentioned, the teeth have here their points made with cylindric profiles, *n r*, *s o*, *u w*, pairing with the walls of the chamber. Each of these profiles extends through a quadrant, *i.e.* through half the pitch, as does also each section *m q*, *p t*, *v x*, of the circular profile of the root cylinder with which the points of the teeth work in contact while crossing the line of centres. *m q* therefore slides upon *n r*, *u w* on *v x* and so on. The profiles *p n*, *m o*, &c. of the flanks of the teeth are here curtate epitrochoids of the rolling pitch circles. The profile *m o* is described by the motion of the point *n* of the wheel *b* relatively to the wheel *a*, these therefore work together as the wheels move as indicated by the arrows. Root does not use exactly the profile thus found, but a profile falling behind it in the wheel, and this is quite justifiable. He sacrifices the second point of contact certainly, but at the same time he avoids the alternate exhaustion and compression of air which would otherwise occur in the space left between the two points of contact. The exact profiles are only shown in the figure for the sake of simplicity. In designing the wheels they have in all cases to be found, in order to determine the limits within which the actual profile can be drawn. Of Root's two arrangements the first is the better, for it delivers a uniform stream of air, which the second, for the reasons mentioned in connection with Fig. 1, Pl. XXXIII., does not. In both of them the volume of air delivered per revolution very nearly approximates to that of the tooth-ring cylinder.

* Clegg, *Manufacture of Coal Gas*, 5th. Ed., 1868, p. 181. The engraving given here shows wheels of a profile absolutely identical with that of Root's wheels.

§ 97.

Payton's Water Meter.

Plate XXXV. Fig. 1.

Fig. 1, Pl. XXXV. is a schematic outline of a water meter exhibited in the English department of the Paris Exhibition of 1867.* It is a two-toothed chamber-wheel train, the profiles of its wheel teeth being involutes of circles. The line (and normal) of contact NN makes in our figure an angle of $15^{\circ}_{\frac{1}{4}}$ to the line of centres; it is necessary to make this angle small in order that the contact may last sufficiently long, The involutes touching in op extend from m to q and from r to n; within m and r circular arcs of any convenient radius (so long as they do not interfere with the contact) continue the profiles to the bosses of the wheels. The backs of the teeth have for their profiles curves which are very nearly parallel to the involutes and which must lie very close to them in order not to disturb the contact, in order, *i.e.* that the back of one tooth may not foul the point of the opposite one. It is for this reason that the teeth have received their peculiar scoop-shaped form.

Here again a quantity of water, contained in the space behind each tooth, is returned every revolution, so that the delivery of the water, as in Fabry's machines and one of Root's, is discontinuous. This can be seen also from the fact that the point of contact does not traverse the whole profile continuously. The volume of water actually passing through the meter per revolution is again very nearly equal to that of the tooth-ring cylinder.

Whether good workmanship is of itself sufficient so completely to prevent leakage that the apparatus can make an accurate water meter can only be determined by experience. The instrument, unquestionably a very simple one, seems to have been very rapidly received into favour in England.

* *The Engineer*, Feb. 1868, p. 92. ("Epicycloidal Water-meter.")

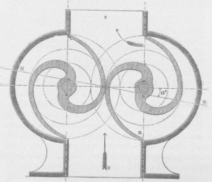


FIG. 1.—Payton.
$(C_{2} C''_{2})^{c}$; $(V \pm) = ab,c.$

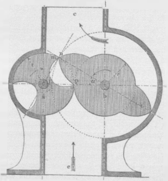


FIG. 2.—Evrard.
$(C_{18} C''_{2})^{c}$; $(V \pm) = b,c.$

§ 98.

Evrard's Chamber-wheel Gear.

Plate XXXV. Fig. 2.

In the Belgian department of the 1867 Paris Exhibition there was exhibited a ventilator of Evrard's which, although very indifferently constructed, was yet in itself remarkable, and deserves notice here. Fig. 2, Pl. XXXV. shows its general construction.

In the Belgian section of the Vienna Exhibition also, one of the same machines was shown arranged as a water-pump. It is essentially a two-toothed chamber-wheel train in which the wheels are not similar in form, although they still, as in the former cases, revolve with equal angular velocities. The wheel *a* has two spaces falling entirely *within* its pitch circle, while the wheel *b* has two teeth lying entirely *beyond* its pitch circle. The teeth of *a* are very similar in form to those of Root's machine Pl. XXXIV. 2, they lie, however, entirely within the pitch circle, the corresponding spaces of *b* therefore are entirely *outside* its pitch circle. The curve *m l o* is the curve described by the point *n* of *b* relatively to the wheel *a*, it is therefore a curtate epitrochoid corresponding to the rolling of the two equal circles of radius *r*. The curve *p n* is the common epicycloid (in this special case a cardioid), described by the point *o* of the wheel *a* relatively to the wheel *b*. Contact ceases at *o* at the instant that *m* and *n* come into gear. In order that this may take place, the angle *m l o* must be made equal to the angle subtended by the foot of the tooth on *b*, that is to double the angle marked *α*.

The spaces of both wheels carry the fluid from below upwards as they turn in the direction of the arrows. The greater part of the contents of the spaces of *a*, namely that represented by the opening *m l o*, is, however, returned again between the wheels. For each revolution, therefore, the volume of fluid passed upwards through the machine is a little less than the volume of the tooth-ring cylinder. The contact of the two wheels has the excellent peculiarity that the tops of the teeth of *a* roll upon the bottom of the spaces of *b* without sliding. The ventilator exhibited at Paris, so far as could be ascertained from a somewhat inaccessible machine, was furnished with straight radial blades instead of the epicycloidal teeth of our figure, which gave sufficiently accurate results for practical purposes, and possessed obvious constructive advantages. The return of a portion of the fluid renders the motion un-uniform, but this, as we have seen, is not a serious drawback to the efficiency of a ventilator. On the whole, therefore, it must be said that Evrard's ventilator is a very practical example of chamber-wheel gear. In order to make its delivery uniform,—so as to suit it better for the purposes of a water-pump or a hydraulic engine,—it is necessary only to give the teeth on *b* circular profiles, and to use the corresponding envelopes for the profiles of the spaces on *a*.

The special form, however, which Evrard has chosen for his chamber-crank chain was known before his invention,—a much older example of it will be described in § 101. The pump constructed on the same principle which was exhibited at Vienna was shown as the invention of Baron Greindl.*

§ 99.

Repsold's Pump.

Plate XXXVI. Fig. 1.

We have seen that the old Pappenheim invention has passed through many changes in the form and number of teeth used. Along with various alterations in the former the latter has been reduced from 6 or more to 4, 3, and even to 2. Only one step more in this really useful reduction could be made, and this has already been taken some years ago in the rotary pump made by

* In England rotary pumps have been made by Laidlow and Thomson, which are founded upon this chamber-crank train in the form in which Evrard used it. *The Engineer*, May 29, 1868, p. 394.—*R.*

Baker's "Rotary Pressure Blower" is kinematically identical with Evrard's machine, but instead of using such a profile for the spaces of *a* as corresponds to the relative motion of the point *u*,—the wheel *a* is made a hollow drum, with a wide opening along the whole length of one only of its sides. It has therefore to revolve twice for each revolution of the fan-wheel *b*, while at the same time a second wheel, in every respect similar to it, has to be added in order to effect the necessary closure with the root circle of *b* when either of the teeth of the latter (which are here also merely thin straight blades) are moving freely across the opening in the drum *a*.

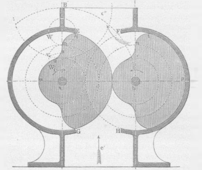


FIG. 1.—Lecocq, Repsold.

$(C_2 C''_2)^c$; $(V\pm) = ab, c.$

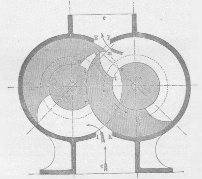


FIG. 2.—Dart, Behrens.

$(C_{,,} C''_2)^c$; $(V\pm) = ab, c.$

the Hamburg firm of Repsold. This well-known machine, which excited great attention in its time, is a chamber-wheel train, the pump wheels of which have one tooth only. Fig. 1, Pl. XXXVI. is a schematic representation of it. The profiles of the teeth beyond the pitch circles are here epicycloids, as *m q* and *nt*, and within them hypocycloids as *ms* and *n r*, both obtained, as in ordinary set wheels, by rolling upon and within the pitch circles (primary centroids) the equal describing circles (auxiliary centroids) *W* and W_1. The portion *s u* of the profile, added at the root of the teeth, is a part of the path of the point *t* of the wheel *b* relatively to *a*; the hypocycloidal arc *m s* corresponds to the rolling of W_1 through the arc *m v*. The points of the teeth *t p* and *q G* are cylindrical, as are also the corresponding surfaces between their flanks, exactly as in the case of common spur wheels. With the profile forms here described the delivery of the pump is not absolutely uniform, for the whole profile of the wheel does not pass continuously through the point of contact. The want of uniformity is so small that it may fairly be neglected; all that is necessary, however, to prevent it entirely is to use in the tooth faces at *m q*, *n t*, &c., such a form as makes the whole profile a continuous curve—as *e.g.* a circular arc—and using for the roots of the teeth the corresponding enveloping form.

The pump-wheels of Repsold's machine are commonly described as "eccentrics of special form" or something of the kind; it is clear, however, from what has just been said, and a glance at the figure makes it still more evident, that each of them is simply a spur-wheel with one tooth. The point and root cylinders of the teeth slide upon one another, so that wear must unavoidably take place at first, as in the Root's blower Fig. 2, Pl. XXXIV. It is therefore difficult to retain a tight joint where these parts of the wheels are in contact, and the pump is therefore most suitable for working with low pressures. The wings *E G* and *F H* of the chamber must be greater than semicircles in order to prevent communication between the suction and delivery pipes behind the wheels. Repsold has used packing strips of leather in them.* The volume of fluid delivered per revolution is almost exactly equal to that of the tooth-ring.

Repsold's pump is used in mining operations, generally for drain-

* *Berliner Verhandlungen*, 1844, p. 208.

ing purposes, and also as a fire-pump; it has also been used in England as a hydraulic motor* (chamber-wheel turbine), and serves often as a gas-pump in gas-works. It has thus been successfully applied to three of the several applications of chamber-wheel gear before enumerated.

So far as the originality of the invention goes—if we may speak at all of the "invention" of what is really only a special form of the Pappenheim chamber-gear—Repsold was not the first to use it, for in France Lecocq obtained a patent for a similar rotary pump in 1832; † he called it a "pump with two pistons revolving on one another."

§ 100.

Dart's or Behrens' Chamber-wheel Gear.

Plate XXXVI. Fig. 2

In the American section of the last Paris Exhibition there were two applications of the chamber-wheel train shown in Fig. 2, Pl. XXXVI.; they were invented by Behrens and exhibited by Dart and Co.‡ The two pump-wheels are here again one-toothed, as in the last case. They are fixed at their sides to circular discs (not shown in our engraving) and this renders it possible to remove altogether the portions of them below the teeth, *i.e.*, the root cylinders. The place of the latter is taken by the cylinders c_1 and c_2, which are fixed to the chamber. These have cylindric hollows, $q\,r$ and $n\,s$, the contact of which with the points of the teeth, as the latter revolve, is sufficient to render unnecessary the additional contact of the flanks of the teeth. In our figure these are shown so as also to work together, mp being a curtate epitrochoid, described by the point o. In practice the point o is left a little clear of the curve (by rounding it off) in order to prevent the compression of fluid in the triangular space $o\,p\,q$. So soon as the point p reaches q, o has got to the same place, and passes downwards from q to r. The point of the tooth of b, therefore, works closed against $q\,r$, while its root t moves always in contact

* *Practical Mech. Journal*, 1855-6, vol. xviii., p. 28.

† *Propagation Industrielle*, vol. iii., 1868, p. 182.

‡ *Propagation Industrielle*, vol. ii., 1867, p. 116. *Engineering*, Apr. 4, 1875, pp. 368–9.

with the cylinder c_2. m soon arrives at n, after which the point of the tooth of a works closed against $n s$, while at the same time the portion of the fluid enclosed between the two wheels is delivered back to $I K$. Meanwhile the fluid has been passing upwards through $I K$ and round c_1, in the left wing of the chamber, while the fluid already above b in the right wing of the chamber has been simultaneously discharged through the delivery opening $E F$.

We notice that here a new idea is brought into the chamber-wheel gear, that of the closure of the central passage by lower pairs (here cylinder pairs),—all the other forms of the Pappenheim machine having used a higher pairing for this purpose. The transition from this to the closure before us may be noticed in the lower pair-closure at the teeth points in the machines of Repsold, Evrard and Root, already examined. So far as closure goes the profiles $m p$ and $o t$ might be omitted; it is, however, well to retain them in order to reduce the quantity of fluid returned, and therefore the un-uniformity of the delivery, as far as possible. The volume delivered for each revolution is again very approximately equal to the tooth-ring volume of one wheel.

On account of the use of lower pairs the prevention of leakage is here more easy than in any of the former cases; the Behrens' machine is therefore well suited for use as a pump. Its manufacturer, Dart (in whose house in New York the inventor Behrens is a partner), has constructed many for that purpose, and also as hydraulic motors,—indeed he has also applied it as a steam-engine. One of these (of 12 H. P. nominal) was at work at the Paris Exhibition, and drove a Behrens' pump.* It may, however, be doubted whether permanently good results can be obtained in this application of the machine, for it will certainly be very difficult to make its working joints tight against high-pressure steam. At best it is far from reaching the completeness, in this respect, of machines of the ordinary form.

At the Vienna Exhibition there was a steam fire-engine in which engine, fire-pumps and feed-pump were all constructed on Dart's plan.

* *Motoren u. Maschinen auf der Weltausstellung* 1867, Vienna, 1868, p. 124.

§ 101.

Eve's Chamber-wheel Gear.

Plate XXXVII. Fig. 1.

The old chamber-wheel train of an American, Eve, gives us what is really the foundation, as to form, of that of Evrard. In this machine (Fig. 1, Pl. XXXVII.), which was patented in England in 1825,* the pump-wheels are essentially two unequal spur-wheels having a diametral ratio 1 : 3. The cylindric axoids of the bodies *a* and *b*, whose shafts are connected beyond the chamber by a pair of common spur-wheels whose diameters are as 3 : 1, roll together at *m n*, while the teeth of the wheel *a* carry the fluid in the direction of the arrow. On the line of centres they pass the space of *b* with higher pair-closure, in precisely the way described in connection with Fig. 2, Pl. XXXV.

In France Ganahl obtained a patent in 1826 for a machine very similar to that of Eve; he intended it both as a motor and a pump.† He made, however, the wheel *b* conical, like the plug of a cock. We can see the idea which led to this form of construction,—the inventor looked upon the wheel *a* as a piston-wheel, and *b* as a valve arrangement. Ganahl's machine is strictly a chamber-wheel train formed from a pair of bevel wheels.

§ 102.

Révillion's Chamber-wheel Gear.

Plate XXXVII. Fig. 2.

The general principle enunciated in § 93 that a chamber-wheel train could be made from any form of the mechanism $(R_z C_2)$ includes also the case of screw-wheels. This has been known for a long time, and many attempts have been made to apply it

* Ewbank, *Hydraulic and other Machines*, 1870, p. 287, also specially Bataille and Jullien, *Machines à Vapeur*, vol. i., 1847-9, p. 440, where other forms are also mentioned.

† *Propagation Industrielle*, vol. iii. 1868, p. 55.

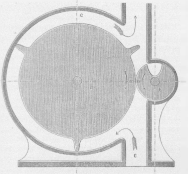


FIG. 1.—Eve, Ganahl.

$(C_z\ C''_2)^\circ;\ V\pm = a, c.$

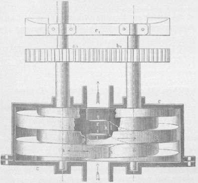


FIG. 2.—Révillion.

$(C^+_z C'''_2)^c;\ (V\pm) = ab, c.$

practically. In 1830 Révillion obtained a patent in France* for a screw-wheel chamber-train. Such a mechanism is shown in Fig. 2, Pl. XXXVII., in a form which differs somewhat from that of Révillion; it is that which I have used for the model in my collection of kinematic models. The wheels *a* and *b* are normal screws of equal pitch and opposite "hand"; their axes are connected by the equal spur-wheels a_1 and b_1; the frame *c* forms the chamber. The outer surfaces of ther threads revolve in (lower) contact with the chamber, the screws work together with higher pairing at *k l*, *m n*, *o p*, etc. I have given them at *q r* and *s t* such a sectional profile that the outer edges of each thread touch throughout the sides of the threads between which it is working (see just above the letters *m n*), which has not been done in any former machines of the kind. The profiles of the cross sections of the threads are envelopes of the helix. The screw cutting lathe makes the accurate construction of these profiles by no means very difficult. The fluid fills the spaces between the threads or teeth, and is pushed forward by the latter just as in the Pappenheim machine. One of these spaces is, for instance, that included between the chamber on the one side and *m n* and *k l* on the other, which is separated from the rest of the chamber by the contact at *q r* and *s t* and at the similar positions on each side of *m n*. The screw-wheel chamber gear can hardly be said to have any practical importance;—I do not think it necessary therefore to consider here any of the other attempts to adapt it to the purposes of a steam-engine or a pump.

§ 103.

Other Simple Chamber-wheel Trains.

The various forms in which the simple chamber-wheel gear can be used have by no means been exhausted by the illustrations we have given, although these include the best known and more important of them. We have seen both equal and unequal spur-wheels used, as well as cylindric screw-wheels, and a suggestion (§ 101) of a pair of bevel-wheels. In this last direction more has been attempted. Herr Lüdecke (Dransfeld, near Göttingen) among others, has constructed a—practically worthless—chamber-

* *Propagation Industrielle*, vol. iii., 1868, p. 151.

train, in which the pump-wheels are equal bevel-wheels with a very obtuse angle between their axes. The interior of the chamber forms a zone of a sphere, and is separated into suction and delivery spaces by two dividing plates in the plane of the axes. The constructive difficulties are here far greater than in the case of the spur-wheels, and, it may be added, this fact has already made itself felt. Spur-wheels, screw-wheels and bevel-wheels have thus already been used in chamber-trains. One variety only is wanting—hyperbolic-wheels—in which the difficulty of making a tight joint certainly reaches its maximum. It is none the less quite possible that any day we may be startled by the appearance of a "hyperbolic rotary steam-engine."

§ 104.

Compound Chamber-wheel Gear.

We examined in § 61 a specimen of compound spur-gearing in the mechanism $(C'_{2}\underset{=}{+}C''_{3})^{e}$ which is represented in Fig. 279. This mechanism has been used as a chamber-train,—by Justice, among others, who employed it as a steam-engine.* Justice, who also constructed a two-wheeled chamber-train, made the four wheels equal, so that *b* and *c* were represented by one wheel only gearing with both the others. The frame *e* was used as a chamber enclosing all the wheels. The design was correct and the construction good, but it is not clear what special advantage could be gained by it.† A compound chamber-train, consisting of four bevel-wheels, was constructed by Davies as early as 1838.‡ It was intended to serve either as a rotary steam-engine or a pump. One of the end wheels, say *a*, had a large tooth extending across to the opposite wheel *d*, and the double wheel *b c* had a slot of which the sides moved in very incomplete closure with this tooth. I have already (§ 91) mentioned this machine, which—intelligibly enough—has long ago been forgotten.

* *Practical Mech. Journal*, vol. xix, 1866-7, p. 360 ; *Propagation Industrielle*, vol. iv., 1869, p. 34.

† For an old chamber-train of three wheels see Bataille et Jullien, *Machines à Vapeur*, vol. i., 1847-9, p. 442.

‡ Newton, *London Journal of Arts, &c.* Conjoined Series, vol. xix., 1842, p. 153.

If the axial distances 1.2 and 2.3 of a compound chain $(C^{+}_{12}C''_{3})$ be made equal, the shafts 1 and 3 may be made conaxial. This gives us the chain represented in Fig. 280, where *b* and *c*, as before, form parts of the same (ternary) link, while *a* and *d* can move

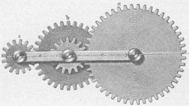


Fig. 280.

independently. We shall call a train of this kind, in which the centres of the last wheel are, as it were, turned back into coincidence with that of the first, a reverted train. This form of train plays no unimportant part in machine practice. Among its other

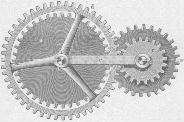


Fig. 281.

applications it has been used as a chamber gear, but in all cases with the variation from the forms already described that it has non-circular wheels,—the chain therefore being $(\bar{C}^{+}_{12}C''_{3})$ and the mechanism $(\bar{C}^{+}_{23}\,C''_{3})^{c}$.

If we make the mean angular velocity ratio of the two wheels *a* and $d=1$, then the non-circular axoids will cause any pair of radii of the wheels to have a relative oscillatory motion, while both are turning continuously in the same direction. Then if two sectors connected with the wheels be enclosed in a chamber formed from the frame *e*, we can use them as pistons; we can pair them, that is to say, with a pressure-organ, either as driven or driving bodies. The relative motions of the two pistons will then be very similar to the motion of those in Fig. 4, Pl. XXI. As a few examples among many, I may mention Smyth's rotary steam-engine, patented in 1838, which had non-circular wheels of complex forms;* Ramey's high-pressure ventilator with four equal elliptic wheels;† and Thomson's steam-engine, with four equal oval wheels, of which two examples were shown at Paris in 1867.‡ The constructive difficulties connected with these machines, especially when they are intended to serve as steam-engines, are so great as to deprive them of practical importance. The outer surfaces of the pistons at least, however, can be made steam-tight, as they form a cylinder pair with the chamber. Ramey's ventilator is said to have given good results.

§ 105.

Epicyclic Chamber-wheel Gear.

I have still one other kind of chamber-wheel gear to analyse, one of which the nature has never hitherto been understood. Even the inventor himself, Galloway,§ does not seem to have known it, judging, at least, from his own description of the connection between his machine and others. In order to make our investigation complete it will be necessary to begin somewhat far back.

By placing the simple train of spur-wheels $(C_z C''_2)$ with which we commenced this part of our analysis (§ 94), upon one or other of the wheels instead of upon the frame, we can obtain two mechanisms, $(C_z C''_2)^a$ and $(C_z C''_2)^b$, besides the one $(C_z C''_2)^c$ already

* Newton, *London Journal of Arts, &c.* Second Series, vol. ix. 1834, p. 152.

† *Génie Industriel*, vol. xxx. 1865, p. 254.

‡ *Rapports du Jury International*, vol. ix., p. 81; *Propagation Industrielle*, vol. iv. 1869, p. 339; *Chambers's Ency.*, 1st. Ed., art. "Steam-Engine."

§ Bataille and Jullien, *Machines à Vapeur*, vol. i., 1848-9, p. 431.

examined They are similar, so we need only examine one of them, say $(C_z C''_2)^s$; this is represented in Fig. 281, where a is supposed to be fixed to the stand. Thenfraruenc becomes a crank

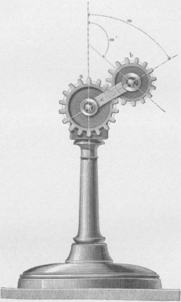


FIG. 281.

turningnabout the axis 1,nwhilethe wheel b rolls upon a. We have first to determine the relation between the angular motions ω' and ω of thenwheel b and the arm c respectively. Imaginethe wheel a to be movable about 1, move it by the crank c, carrying with it b, through any angle ω, and then leaving c in its new position turn a back into its old one. Then any diameter of the wheel b will have first turned through an angle ω from its original position, and will then (considering the diametral ratio $\frac{a}{b}$ of the wheels) have been further turned through an angle of $\frac{a}{b} \times \omega$, both rotations taking place in the same direction as that of the arm,—so that the whole angular motion of b has been :—

$$\omega' = \omega + \frac{a}{b}\omega = \omega\left(1 + \frac{a}{b}\right).$$

If for any given time, as a minute, $\omega = n.2\pi$ and $\omega' = n'.2\pi$, we have for the relative number of revolutions of the wheel and the arm :

$$\frac{n'}{n} = 1 + \frac{a}{b}.$$

If either of the wheels were annular, then the turning back of a into its original position would diminish instead of increasing the angular motion ω' of b, so that we should have

$$\frac{n'}{n} = 1 - \frac{a}{b}.$$

Such a mechanism as that before us is known generally as an epicyclic train. It is frequently applied in practice in the form shown, but more often still in a different shape, that namely of a reverted epicyclic train.

If we place the reverted train $(C_{z3}\, C_3')$, already considered in the last section, upon a, as is shown in Fig. 282, we can find the velocity of the turning link $b\,c$ by the foregoing method. It is now necessary however to find the motion of the wheel d (conaxial with a) relatively to that of the arm. Using the same method as before we see that while d is carried forward through ω by the action of the arm, it is caused to turn $\omega \times \frac{ac}{bd}$ in the opposite direction as a is moved back to its original place,—so that the actual total angular motion of d is:

$$\omega_1 = \omega\left(1 - \frac{ac}{bd}\right)$$

and we have for the relative number of turns per unit of time of the wheel d and the frame e:

$$\frac{n_1}{n} = 1 - \frac{ac}{bd}$$

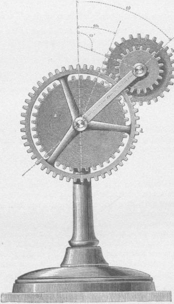


FIG. [illegible]

The mechanism $(C_{x2}C_3'')^a$, which we have thus obtained by the simple inversion of a kinematic chain, is frequently called in machinery differential gear. This name has apparently been chosen because of the minus sign in the last formula. We shall not retain it, for it may occasion misunderstanding, but shall call the mechanism a compound (reverted) epicyclic train.

If there be an annular wheel in either of the two pairs of wheels a, b and c, d, the formula for the relative rotations will be:

$$\frac{n_1}{n} = 1 + \frac{ac}{bd}.$$

If each of the two pairs contain an annular wheel* it is again

$$\frac{n_1}{n} = 1 - \frac{ac}{bd}.$$

Or generally, if we indicate the simple velocity ratio of the train of wheel work by a, we obtain the formula

$$\frac{n_1}{n} = 1 - a.$$

Here a itself is positive if there be two annular wheels or none, the minus therefore remains; while if there be one annular wheel only a becomes negative and the sign in the formula is positive.

There are many forms and still more applications of the mechanism before us. It will be noticed that in cases where a is negative in the formula and > 1,—the rotation of d is in the opposite direction to that of e. To simplify the description we shall call a the first and d the second central wheel and b the first and c the second outer wheel.

The limiting cases which occur when some of the wheels are made infinite are very important. One of these I must specially examine, it is as follows. Let us suppose that either of the wheels a or b be annular, as in the diagrams Fig. 283, in which the pitch circles only are shown; then a is, as we know, negative, and the expression for $n_1 : n$ is

$$\frac{n_1}{n} = 1 + \frac{ac}{bd}.$$

Let, however, the radius of the annular wheel be infinite, then in order to gear with it the other wheel of the pair must be infinite also. The centres of the two infinite wheels lie within the finite

* As, for example, in Moore's pulley-block,—illustrated in *Engineering*, Sept. 17, 1875.

ones, namely at 1 and 2, but their points of contact, and indeed the whole of their teeth are beyond our observation; they disappear from the mechanism, and only the two finite wheels *c* and *d* remain. The epicyclic train is thus reduced by two wheels, of which one revolves about 1, while the other turns round the first, carried by the frame *e*. The form at which we have arrived is different from that of Fig. 281, for there the central wheel *a* was fixed, while here the only central wheel left, *d*, turns about its axis. In order, however, that the chain may remain closed, it must contain some representative of the wheels which have disappeared. The use of the latter has taken the point of contact, or instantaneous centre, to an infinite distance; it will be seen therefore that they

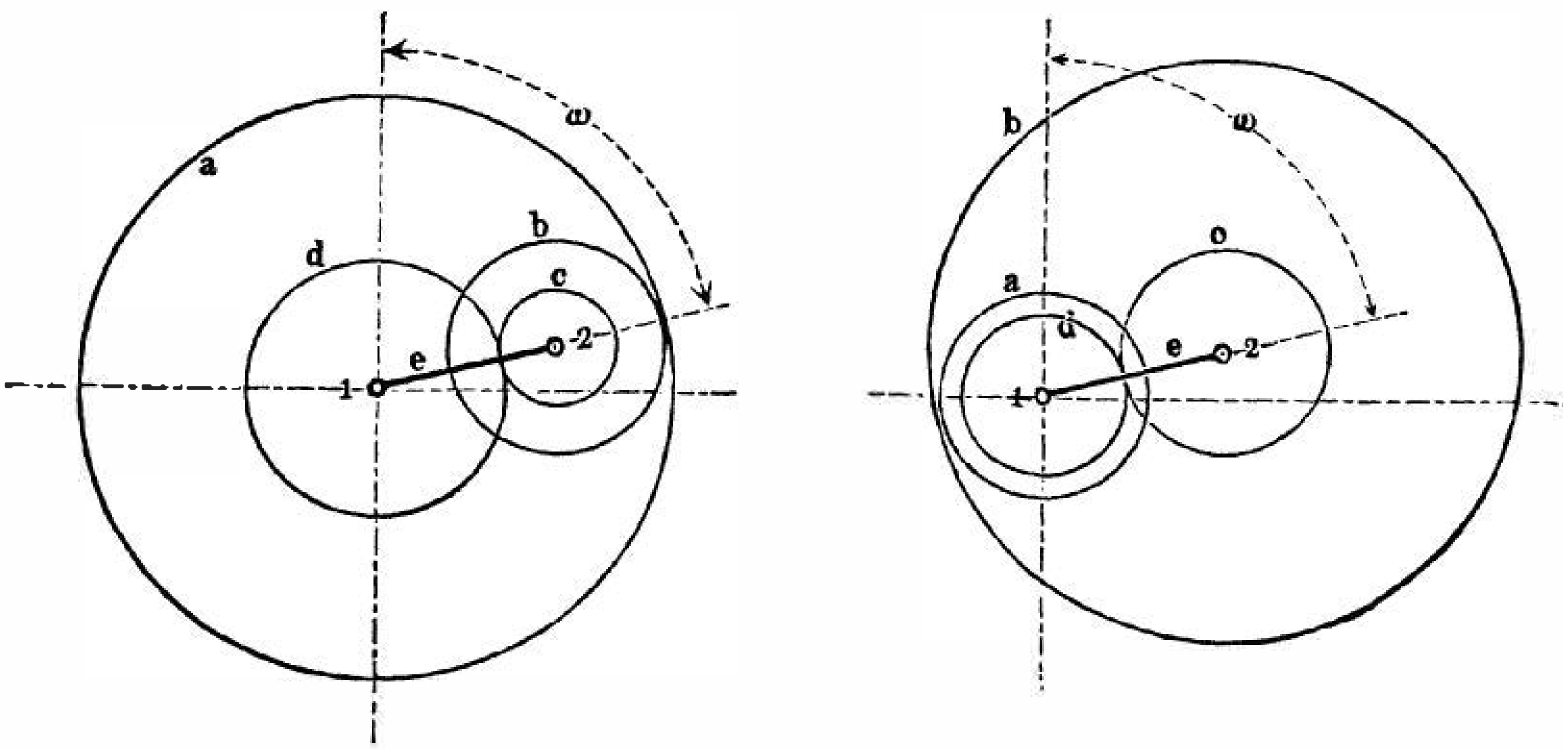
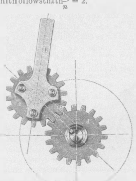


FIG. 283.

may be replaced by any arrangement which will prevent the wheel *c* from making any rotation about its own axis, by means of which, that is, its motion may be restricted to one of translation only, every line upon it moving parallel to itself. This might be done by the addition of a kinematic chain (which we may call accurately a parallel train or motion), so attached to *c* as to constrain it in the required manner.

It is evident, however, that so far as the total motion (in each period) of *d* is concerned, *c* may be allowed to oscillate about its centre 2 to a certain extent, so long as it never completely rotates. This is exactly what occurs in Watt's "Sun and Planet" wheels, Fig. 284, where the upper end of the connecting rod *b* is connected to the beam, and the wheel d fixed to the connecting-rod oscillates with it, but never turns. This mechanism of Watt is therefore a special form of the epicyclic train $(C_{z2}C_3'')$*. Watt usually made $c = d$, from which it follows that $\frac{n_1}{n} = 2$.



There is nothing here to prevent the use of an annular wheel as one of the pair c d. If this be done a becomes negative. If the outer wheel c be made the annular wheel, the value of a is always greater than unity, and the direction of rotation of d is negative *i.e.*, it turns in the opposite direction to the frame e *

Galloway's rotary steam-engine, now to be described, is simply a chamber-wheel mechanism formed upon a planet-train like that of Watt with an annular outer wheel.

The following three figures represent three forms given by Galloway to his engine, which he intended for screw propulsion

* Watt himself in his first specification mentioned specially the application of an annular wheel in the sun and planet gear. Muirhead, p. 50. See also Bourne's *Treatise on the Steam-Engine*, p. 21. R. [There is now in the Patent Museum at South Kensington a model of Watt's in which the connecting-rod end is made an annular wheel. To keep this in gear with the wheel on the shaft there is a small roller placed upon a pin attached to its lower part, and this is made to roll upon a suitably shaped cam touching it always on the side furthest from the point of contact of the wheels themselves.]

I have placed on the figures our reference letters to enable the different parts to be more easily distinguished. In the three-cornered piston of Fig. 285 we have a spur-wheel with three teeth, the central wheel d of the planet-train Fig. 284, and in c we have the corresponding four-toothed outer wheel, which is here annular. In order that the motion of the wheel c, which is also the chamber, might be one of translation only, Galloway carried it (quite correctly so far as the required motion is concerned) on three equal and parallel cranks $e\,e\,e$. We can easily recognize in these the mechanism $2\,(C''_2 \parallel C''_2)^a$ which we have already analysed in § 66. The proper internal profile of the chamber gave the inventor


FIG. 285.


FIG. 286.


FIG. 287.

much trouble. It is, in reality, simply the profile of the teeth of a four-toothed wheel such as can work in gear (and indeed in steam-tight contact!) with the three-toothed pinion wheel d. The inventor, although he starts from the idea of the annular wheel in his explanation, does not treat the bodies c and d as toothed wheels; but says expressly: "What I propose is to substitute for toothed wheels, in the majority of cases, the arrangement shown in the figures, which I shall now explain. . . ." The figures show distinctly enough that the space between the teeth of c and d varies periodically from a maximum to a minimum, and is therefore suitable for use with a pressure-organ which can be alternately admitted to and discharged from it. For the relative rotations of d and e we have $\frac{n_1}{n} = 1 - \frac{4}{3} = -\frac{1}{3}$, *i.e.* for three revolutions of the centre of the chamber, or (what comes to the same thing) of the small guiding cranks e, the piston d revolves once in the opposite direction. Galloway proposed to connect one of the cranks with the screw-shaft of the vessel, in order that this might rotate three times as fast as the piston. In Fig. 286 $\frac{n_1}{n} = 1 - \frac{3}{2}$, in Fig. 287 $1 - \frac{5}{4}$. The inventor points out that the parallel cranks may be connected to the "piston," and the chamber made to revolve in fixed bearings, which is equivalent to making *c* an ordinary spur-wheel and *d* an annular wheel, so that $1 - a$ again becomes positive.

It is sufficiently obvious that this machine is without practical value as a steam-engine, although Galloway prepared a design for a 300 H.P. marine engine on his system. Kinematically, however, it is none the less instructive. In connection with it and the preceding examples our analysis has, I think, shown once more its capacity for completely solving constructive riddles. These examples at the same time furnish another illustration of the remarkable tendency which has so often shown itself in machine-practice to run through whole circles of solutions for one and the same kinematic problem by a series of isolated and entirely independent attempts. On account of their very isolation these attempts have often, as we have seen, led to extraordinary results arrived at by most roundabout methods. Notwithstanding the simplicity of the real relation between these mechanisms, which our analysis has now shown us, we can comprehend in the fullest degree how much greater the difficulties of the various inventors have been than the results they have obtained by overcoming them.