

III.—*Researches on the Vacuum.*

By HERMANN SPRENGEL, Ph.D.

1. *The Instruments.*

THE methods hitherto proposed for producing a vacuum may be divided into two classes, the mechanical and the chemical. A gas which fills a space may either be removed mechanically, or it may be converted, by taking advantage of its chemical or physical properties, into a non-gaseous, tensionless body. As however our atmosphere, from its general presence, is for the most part the only gas which has to be considered when a vacuum is to be formed, and as the reduction of its constituents to the non-gaseous form is attended with peculiar difficulties, I am inclined to consider that all practical methods of producing a vacuum may be regarded as mechanical. Atmospheric air may in fact be expelled from a space, firstly, by a solid

* Chem. Soc. J., vol. ix, p. 1.

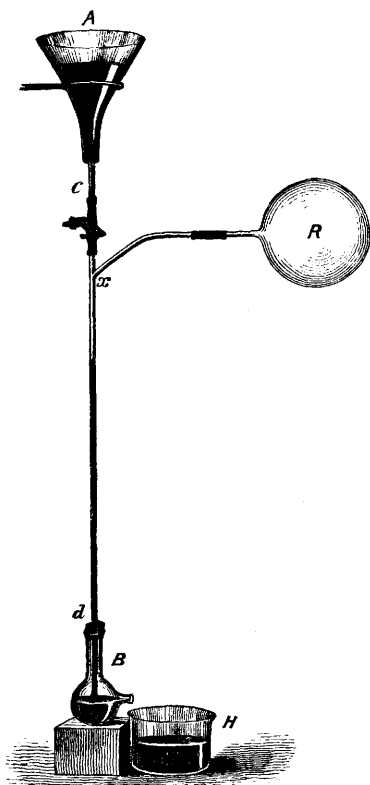
body, secondly, by a liquid, and thirdly by a gas, which afterwards takes either a liquid or a solid form. Perfect vacua have hitherto been obtained only by this last method, but with such attending difficulties, that it appeared to me highly desirable to improve the other two, which afford greater facilities of working. The displacement of a gas by means of a solid or a liquid body is effected by instruments, commonly called air-pumps. The exhausting syringe of Otto von Guericke, with its piston, is the type of one class of these instruments, while Toricelli's barometer, with its column of mercury, is the type of the other class. The invention of the common air-pump was a consequence of Toricelli's vacuum, and it is partly due to this, that the degree of exhaustion attained by it has been, up to the present day, compared with Toricelli's vacuum as the standard of perfection. Hence it has followed that physicists have from time to time attempted to use Toricelli's vacuum as a receiver, or in other words to fill receivers with mercury, and attach tubes to them as long as those of barometers, through which the mercury was allowed to run off. All so-called mercurial air-pumps are based upon this principle, and differ very little from the famous experiment which Toricelli made 220 years ago.

This, however, is not the only way in which the case may be viewed. If the top of a barometer were knocked off, the air would enter and the mercury would sink, or what is the same, the mercury would sink and draw in the air. If, however, the experiment be so arranged as to allow air to enter, together with the mercury, and in such a manner that the supply of air shall be limited, while that of mercury is unlimited, the air will be carried away, and a vacuum produced. It is upon this principle that I have constructed a pneumatic machine, of which Fig. 1. represents the simplest form.

cd is a glass tube, longer than a barometer, open at both ends, and in which mercury is allowed to fall down, supplied by the funnel *A*, with which the tube is connected at *c*. The lower end, *d*, of this tube dips into a small glass bulb, *B*, into which it is fixed by means of a cork. This glass bulb has a spout at its side, situated a few millimetres higher than the lower end of the tube *c d*. The first portions of mercury which run down, will consequently close the tube, and form a safeguard against the air, which might enter from below, if the equilibrium should be disturbed. The upper part of *cd* branches off at *x* into a lateral

tube, to which the receiver *R* is affixed. As soon as the stop-cock at *c* is opened, and the mercury allowed to run down, the exhaustion begins, and the whole length of the tube, from *x* to *d*, is seen to be filled with cylinders of mercury and air, having a downward motion. Air and mercury escape through the spout of the bulb *B*, which is above the basin, *H*, where the mercury is collected. This has to be poured back from time to time into the funnel *A*, to pass through the tube again and again, until the exhaustion is completed. As the exhaustion is progressing, it will be noticed that the enclosed air between the mercury cylinders becomes less and less, until the lower part of *c d* presents the aspect of a continuous column of mercury, about 30 inches high. Towards this stage of the

FIG. 1.

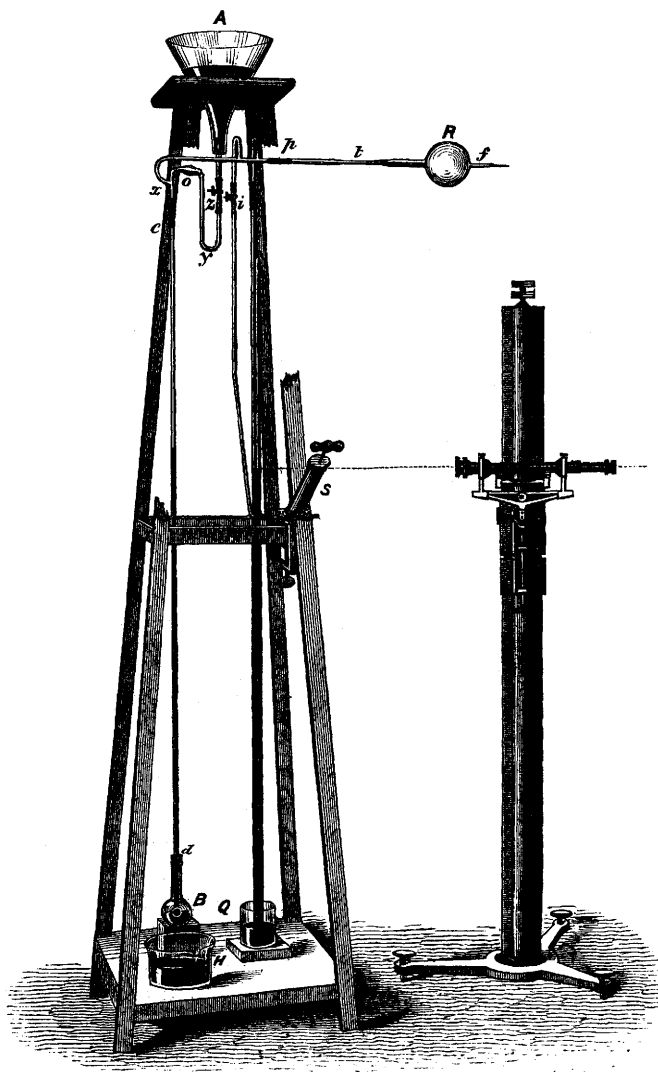


operation, a considerable noise begins to be heard, similar to that of a shaken water-hammer, and common to all liquids shaken in a vacuum. The operation may be considered completed, when the column of mercury does not enclose any air, and when a drop of mercury falls upon the top of this column without enclosing the slightest air-bubble. The height of this column now corresponds exactly with the height of the column of mercury in the barometer; or, what is the same, it represents a barometer, whose Toricellian vacuum is the receiver *R*.

Fig. 2 represents the actual instrument, with which I am in the habit of working. The funnel *A*, supported by a wooden stand, serves as the reservoir for the mercury. By means of the tube *z y x*, it is connected with the tube *c d*, which I call the

"fall tube," so that the mercury will run down, as soon as the clamp z is opened, which compresses a caoutchouc tube inserted

FIG. 2.



there. The tube $x p$ leads to the receiver, which is to be exhausted, and is in connection with two tubes, one of which is attached to

the common exhausting syringe *S*, while the other, serving as a guage, dips into a glass of mercury, containing a barometer. When the instrument is at work, the rising of the mercury in this guage will consequently show the degree of exhaustion. The exhausting syringe is merely attached as an auxiliary, to accelerate the operation, because the fall-tube, for a reason to be presently mentioned, must be of a thin calibre. The greater portion of air is more quickly removed by the syringe, and after this has been done, as much as possible, and the connection between the receiver and the syringe has been broken off by compressing an inserted caoutchouc tube with the clamp *i*, the remainder of the air is carried off by the running mercury. The bulb *B*, and the basin *H* are exactly as in Fig. 1. The instrument is about 6 feet high, so that the mercury collected in the basin *H* can easily be poured back into the funnel *A*. The use of a pump would facilitate the raising of the mercury, and prevent the admixture of air. This latter inconvenience may, however, be pretty well overcome by gently pouring the mercury on a glass plate, floating on the surface of that in the funnel. Should a few air-bubbles attach themselves to the side of the funnel, it may be best to remove them by means of a wire or a glass-rod, though they are not, perhaps, of much consequence, as they are not observed to pass along with the mercury. The connections between the glass tubes are made of well-fitting black vulcanised caoutchouc tubing, sold under the name of "French tubing." This is free from metallic oxides, which render the tubing porous. Besides this, all these joints are bound with coils of copper wire, which is easily accomplished with a pair of pliers. Moreover, the space between the inside of the caoutchouc tubing and the outside of the glass tubing, is filled with a resinous cement made of fused caoutchouc. To prevent this substance soiling the interior of the instrument, I first, after having put the instrument together, tie the caoutchouc joint with the copper wire, and then turn back the end of the caoutchouc tubing over the coil, coat the inside of the end with the cement, and turn it back again into its proper position. From this it is obvious that the fused caoutchouc can only penetrate as far as the copper wire coil. The connection of the funnel with the tube *z y o* is made by means of a perforated caoutchouc cork. (These corks are easily made from a flat block of caoutchouc, cut out with a sharp Mohr's cork-borer, well lubricated with oil). When the instrument has been put together in this manner, it is ready for

use. At first the mercury is allowed to enter the fall-tube in such quantities as to raise the mercury in the guage as quickly as possible. When, however, the operation approaches its completion, which is shown by the rattling noise, it will be found useful to lessen the supply of mercury, and to let it fall down drop by drop on the column of mercury in the lower part of the fall-tube, and to proceed in this way till the exhaustion is completed. I am not able to give any definite statement as to the quantity of mercury to be employed, as it is obvious that a small quantity, say an ounce or two, is capable of exhausting a receiver of an indefinite size, if this mercury is only made to pass the fall-tube often enough; but I may remark that I have found 10 to 15 lbs. of mercury a convenient quantity to work with.

In my endeavours to find out how to construct the instrument, in order to exhaust a receiver, with the greatest economy of time and mercury, I have not met with satisfactory results. There, of course, exists a certain relation between the amount of air to be exhausted, the quantity of mercury to be employed, and the time of the operation. In order to make the instrument act at all, the supply of mercury must be at least so large that the fall-tube may become closed, *i. e.*, the running mercury may form drops of a cylindrical shape, breaking off the communication between the receiver and the external air. As the supply of mercury is increased, the rapidity with which the air is carried off also increases. But this soon reaches its limit, as, should the mercury be admitted too rapidly into the fall-tube, it gains the preponderance, and closes the aperture at *x*. The most favourable conditions under which the instrument might be used are those where the mercury is made to fall down drop by drop, enclosing between every two drops as large a portion of air as possible.

Volume may be increased by extension either in height or in breadth. If the fall-tube be lengthened, the bulk of the enclosed air will be increased, and the time required to produce exhaustion will be shortened, without increasing the weight of mercury employed. But as it is inconvenient to have the instrument higher than the height of a man, I attempted to increase the second dimension, *viz.*, the width of the tubes. I soon found, however, that it was difficult, if not impossible, to close tubes of more than a certain width by single drops. In order to close a wide tube with a cylinder of mercury (or any other liquid), the mercury (or this other liquid) must run in freely and not in drops, for the simple

reason that drops cannot be formed of the diameter of the calibre of the tube. The size of the drops depends, upon the specific attraction of the molecules of the liquid, the form and surface of the vessel from which the liquid drops, the attraction existing between the liquid and the vessel, and the resistance offered by the greater or less density of the air through which the drop falls. I have not been able to form in a vacuum drops of mercury larger than about 3 millimetres in diameter.

Having failed in the use of a wide fall-tube, I endeavoured to effect my object by the use of several small fall-tubes. Here, however, another obstacle offered itself. It is exceedingly difficult to regulate the flow of mercury so evenly that exactly the same quantity shall run down in each separate fall-tube, and I have found in practice, that unless the flow of mercury can be so regulated, simultaneous action cannot be obtained in the fall-tubes.

From these experiments, I have found myself unable to produce a vacuum as quickly as with a common exhausting syringe, unless by the employment of inconveniently large quantities of mercury at a time. If speed is required, I think the fall-tube should have the addition of the exhausting syringe, which will take away more quickly the larger quantity of air and leave to the running mercury only the task of completing the exhaustion. By such a combination, however, the instrument loses much of its simplicity, and offers by its numerous joints a far greater chance of leakage. For this reason, where time is no object, it will be preferable even to do without the gauge and to use the instrument in its simplest form, as represented in Fig. 1. The operator will soon learn from observation of the way in which the drops fall down, when the exhaustion is completed. Without the auxiliary air-pump, the exhaustion of a receiver of the capacity of about half a litre will take from 20 minutes to half an hour. Though this may appear to be a long time, I have no doubt this method will be found after all, the quickest and simplest, for producing a vacuum as nearly perfect as I have been able to produce.

The slowness of the action is obviously due to the smallness of the bore of the fall-tube. As soon as the calibre of this tube is increased, the time of the operation rapidly decreases: for the contents of two cylinders of the same height are to each other as the squares of their radii, and the time of the operation ought to decrease in the inverse ratio. The proper size of the bore of the fall-tube is $2\frac{1}{2}$ to $2\frac{3}{4}$ millimetres. As soon as I exceeded this

limit, I invariably found the vacua less perfect. It is not difficult with these wider tubes to raise the mercury in the gauge to the height of the barometric pressure, minus 1 or even $\frac{1}{2}$ millimetre; but I have not been able to obtain with them vacua so near perfection as I have been enabled to obtain by the use of fall-tubes of $2\frac{1}{2}$ millimetres calibre. The explanation of this fact must be sought for in the size of the drops, which, as it appears to me, must, in falling down, exercise a certain pressure against the side of the tube thereby preventing the denser air underneath the drop from finding its way again to the part of the tube above the drop, where the air is more rarefied. I have not obtained better vacua by the use of fall-tubes of a calibre less than $2\frac{1}{2}$ millimetres.

Before I proceeded to test the efficiency of the instrument, I directed my whole attention to the construction of air-tight joints; in this, however, I did not succeed. It is a well-known fact, that barometers become inaccurate in time, as air finds its way into the Toricellian vacuum between the glass and the mercury enclosed in it. The vacuum in my instrument is of course exposed to the same sources of imperfection. (To offer a greater resistance to the air, which might enter from the funnel, I have given to the tube *zyo* the form of a U tube.) Leakage, however, happens in a far less degree from this cause, than from the imperfection of the caoutchouc joints. Among the numerous modifications I have tried, I consider the one which I have before described, as the most practicable. With this joint the mercury in the gauge does not sink more than about $\frac{1}{2}$ millimetre in 24 hours. Williamson and Russell,* in constructing their admirable apparatus for the analysis of gases, have met with the same difficulty, and I am able to corroborate their statements. The porosity of solid bodies is astonishing, and one is almost compelled to think that glass vessels are the only ones impenetrable to gases.

The following degrees of exhaustion have been made with cold mercury, which had merely been filtered through paper to free it from visible impurities, but which had neither been dried nor freed from air by special means. I have worked with heated mercury (100 to 150°C.), but have not noticed much difference in the perfection of the vacua. Even if some slight advantage could be obtained by it, its use would be objectionable, practically speaking, from the risk of endangering the health of the

* Chem. Soc. J. [2], ii, 238.

operator. When the mercury is heated and allowed to run down quickly, the instrument is at the same time converted into a sort of electric machine. In the dark, flashes of electric discharge are seen to light up the exhausted tubes, and sparks may be drawn at intervals from the basin in which the mercury collects, as from an electrophorus. The fall-tube invariably becomes soiled after some time by some impurity in the mercury, and particularly after the employment of heated mercury. I attribute this to the oxidation of the mercury, arising from this electric action, which must be favourable to the formation of ozone. I have to mention, that to attain high vacua, the fall-tube must be clean as well as the mercury.

The length of the fall-tube in the instrument before us is calculated for the use of a liquid having the specific gravity of mercury. Of course, as the specific gravity of the liquid employed becomes less, the fall-tube must be longer. Practically, however, water is the only liquid that need be considered in place of mercury, and I have no doubt that an instrument adapted for water would furnish a simple and most efficient exhausting machine. It is not unlikely that such an instrument might possess advantages which air-pumps of other constructions have not, particularly in hilly countries, where the large volume of a natural waterfall might be rendered available.

I now come to consider the way in which this instrument acts. It is obvious, that it stands in a near relation to the *Trompe* or *Catalonian bellows*, the old and well-known contrivance for producing a blast. My instrument is merely the reverse of the trompe, with this addition, that the supply of air is limited, while that in the trompe is unlimited. The theory which explains the action of the trompe, will at the same time explain the action of my instrument. The theory of the trompe has repeatedly been treated by distinguished philosophers, as Venturi, Magnus, Buff, and others. It would lead me too far to enter upon a criticism of their opinions, which appear to me partly erroneous, partly not to the point. In my opinion, the action of both instruments may, in all cases, be satisfactorily deduced from Kepler's law of the uniformly accelerated motion of bodies. When the clamp z is opened, only a certain and almost uniform quantity of mercury (or any other liquid) can pass at a given time. As soon as a particle of mercury has arrived at x , it is under the influence of the general law of gravitation. It must sink and move with uniformly accelerated

velocity. The same may be said of the second or third particle of mercury; but while the second one is starting, the first one has accomplished a portion of its way, and when the third is starting the distances between one and two and two and three are not equal, but unequal. A vacuum must, therefore, have been formed between them, and hence the tendency of the air to restore the disturbed equilibrium, *i.e.*, by rushing in, if the instrument is open, or by expanding, if a receiver is attached. If the tube into which the liquid runs is larger than the column of liquid which the atmospheric pressure can support, the air in the receiver will of course expand to its last degree. If the mercury is allowed to fall down in *c d* in drops, it will act in exactly the same manner as the piston in a common air-pump. These drops are, so to speak, liquid pistons.

The chief excellence of this instrument appears to me to be its simplicity and the great perfection with which it performs its work. To ascertain the degree of exhaustion, I had at first to resort to a comparison with the barometer but I have not been able to make a barometer, in which the mercurial column stood higher than in the gauge of my instrument, though the barometers were constructed with care, and the readings made by means of a cathetometer. Though my instrument was not airtight, and consequently not perfect, this apparent equality of the levels in the gauge and in the barometer, is easily accounted for, upon reflection, by the fact that the human eye is not able to distinguish between $\frac{1}{100000}$, or even $\frac{1}{10000}$ part of a millimetre. But being curious to see how much the instrument, even in its present imperfect state, can do, I have taken particular pains to ascertain it; I have tried different ways, but I will describe only that which appears to be the best and most efficient. It is simply the application of Dumas' method for the determination of vapour-densities. I took a receiver of the form *R* (Fig. 2), a bulb extended on both sides into a capillary tube, one of which was open and attached to the instrument, while a portion of the other was broken off and the aperture sealed. The part taken off, and having consequently the same calibre as the portion left attached to *R*, was preserved. The receiver was now exhausted and taken off by sealing it at *A*. This point was broken under the mercury which had just run through the instrument. I did this to meet the objection, that boiled mercury might absorb the remainder of the air in *R*, while, on the other hand, mercury containing more air

might give off some of it and allow it to enter the vacuum. If, now, the receiver had been perfectly exhausted, the mercury would have filled it completely. This however was not the case, a very small air-bubble always remaining at the end of the sealed capillary tube. The capillary tube was broken off at f , and the mercury contained in R was collected and weighed. Into the capillary tube, first broken off from the receiver, I now introduced by suction a small particle of mercury of exactly the same length as the particle of air in f . This mercury was then placed in a delicate balance and weighed. The weight of this particle of mercury bears the same proportion to the weight of mercury in R as the weight and volume of air remaining in R , after exhaustion, bears to the weight and volume of air in R before exhaustion. The highest proportion I have attained in this way is $\frac{1}{1300000}$, and upon the average I consider it not a difficult thing, with the present means, to exhaust a receiver to $\frac{1}{1000000}$. From this it is obvious that a barometer may be made by simply exhausting and sealing a tube, one end of which is then broken under mercury. I have actually made some in this way.

I have applied the finest reaction for the presence of gases, viz., the absence of any electric discharge in a perfect vacuum.* The few tubes I have made hitherto always showed a slight discharge, which, however, I have chiefly attributed to the presence of mercurial vapour, though I could have ascertained it by means of spectrum analysis. I have tried to remove this vapour by introducing, between the instrument and the electrical tube, a tube exposed to a cold of -10° C., or filled with finely divided gold or freshly ignited charcoal, but the intensity of the whitish-green electric light appeared to be not much diminished by these means. From this I infer that the mercurial vapour has either not been condensed, or the supporter of light is due to another body. Being aware of the subtlety these experiments require, and of my shortcomings in their performance, I should not like to say more about them now, but I hope to repeat and study them with care hereafter. At any rate, I have learned this much, that during the exhaustion with my instrument, the colours of the electric discharge change from intense red and blue to faint white and green; that I have passed the limit at which the density of the air is most favourable to the electric discharge; that the stratifications are exhibited in an admirable

* Gassiot, Phil. Trans., 1858-9.

manner; and that the instrument will prove useful for the performance and study of these experiments, which on account of their beauty have excited so large an interest.

Before concluding this paper, I should like to say one word more about the theory of the action of the instrument. Is the action entirely due to the accelerated velocity of the mercury and the elasticity of the air? I answer, yes. Struck by the extraordinary attenuation of the air, and misled by Venturi's theory, I was at first much inclined to attribute the action partly to two other agencies: the attraction of gases to liquids, and their absorption by liquids. But the following experiments showed me that I was mistaken. I forced water through short *T*-pieces at different velocities, using from a slight pressure up to that of several atmospheres, and I have not been able to raise water in a tube connected with the other branch of the *T*-piece to a greater height than that corresponding to the length of the tube from which the water was expelled. But this does not show so much as the fact, that when the calibre of the fall-tube is larger than $2\frac{1}{2}$ millimetres, it is impossible to raise the mercury in the gauge so high as it stands in the barometer, however long the mercury may be allowed to run, and whatever quantity may be used. This shows that the action is entirely mechanical, that the air expands and is cut off, portion by portion, by the falling drops of mercury, and that when the air is highly attenuated, these drops must entirely fill the tube, and even exercise a slight pressure against the sides of the fall-tube, otherwise the action will cease, as in a common air-pump, through the non-action of the valves.

I am under the impression that the use of better materials, and the application of greater skill than I have hitherto employed, will be followed by still better results, and will not improbably furnish instruments capable of producing vacua perfect to our senses; and even if we should not succeed in making a perfectly air-tight joint, the end will still be attained, if we can only succeed in carrying off the air more quickly than it can enter. At any rate, the immense elasticity of air is here displayed in a striking manner, and there is a very wide interval between the attenuation of 1,300,000, to the density of gases which must exist in the powder-chambers of cannons or mines at the moment of explosion. Another striking fact is that exhaustion of $\frac{1}{1000000}$ has been made with cold common mercury, doubtless containing a considerable quantity of air and moisture, which one would expect to be set free

and enter the vacuum as soon as the mercury so violently agitated passes along the fall-tube. But the particles of these absorbed gases, which are set free on boiling, must, at common temperatures, be so intimately connected with the mercury, that their expanding or gaseous properties are lost, as in the oxygen of oxide of mercury.

The main fact which I have established in this paper may be shortly stated to be that, *if a liquid be allowed to run down a tube, to the upper part of which a receiver is attached by means of a lateral tube, and if the height at which the receiver is attached be not less than that of the column of the liquid which can be supported by the atmospheric pressure, a vacuum will be formed in the receiver, minus the tension of the liquid employed.*

The properties of highly rarefied gases, and the conditions of that remarkable space in which there is *nothing*, have hitherto been scantily examined, though this subject is suggestive of interesting questions, the solution of which I hope to treat of in my further investigations that border on the, so to speak, negative side of natural philosophy.

The above experiments* were performed in the laboratory of St. Bartholomew's Hospital, and I am glad to have the opportunity of acknowledging most gratefully the facilities which have been offered to me by Dr. Odling in the prosecution of them.

The instrument may be seen at Elliott Brothers, Strand, London, from whom it may be obtained.
