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"THE STEAM INJECTOR."

BY

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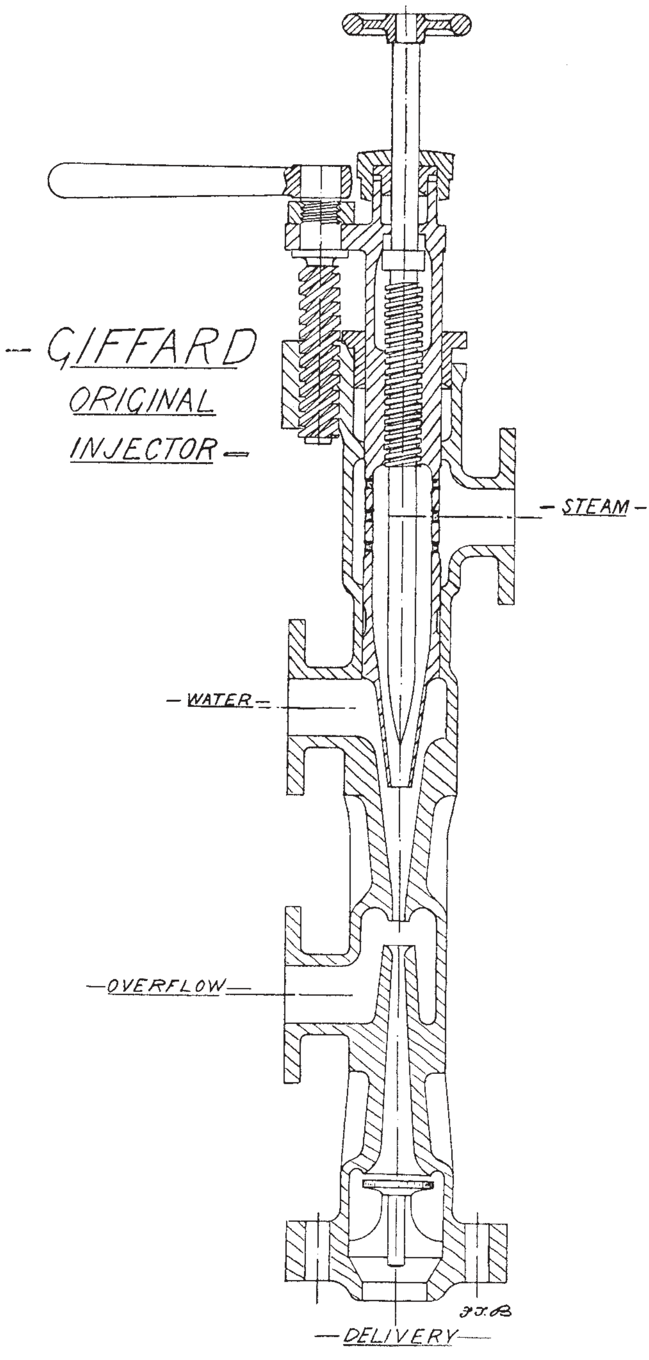
In endeavouring to trace the history of the injector it will be found that as early as 1570 there is a record of the use, by Vetrio and Philebert de Lorme, of a crude ejector apparatus, but it was not until the birth of the nineteenth century that anything bearing any resemblance in principle to the injector made its appearance. Then, however, Mannoury de Dectot used steam to raise water, the combined jet playing on a paddle wheel in an arrangement which was patented on August 15th, 1818 ; but it is to aviation that the engineer owes the injector proper.

Monsieur Henri Giffard, when engaged in a series of experiments on the use of steam engines as a means of propulsion for dirigible balloons, experienced difficulty with regard to the weight of pumps required to feed the boiler. To get over the difficulty he conceived the idea of utilising a jet of steam to force water into the boiler. This was in 1849 but the instrument was not made until six years later, in the same year as Bourdon (of pressure gauge fame) took out a patent. Priority was finally settled in Giffard's favour.

The Giffard injector is illustrated in Fig. 1. Steam from the boiler travels down past the regulating spindle, through the steam tube, cone or nozzle, as it may be alternatively termed, to meet the water which comes along from the feed tank. It is condensed and combining with the water imparts its momentum to the resultant jet, which suffices to force it into the boiler. The theory of operation will be described later.


GIFFARD
ORIGINAL
INJECTOR
STEAM
WATER
OVERFLOW
DELIVERY

The three nozzles are termed the "steam nozzle," the "combining nozzle" and the "delivery nozzle" respectively.

To start the injector steam is admitted in a small quantity by turning the screw to raise the needle a little. This admits a small quantity of steam which, meeting with the water, is condensed but has not sufficient energy to open the clack valve and enter the boiler. The hot water therefore escapes through the overflow gap provided. The needle is then gradually withdrawn and the jet in gaining momentum opens the clack and enters the boiler.

Were the needle withdrawn at once the area of the steam jet would be in excess of the smallest area of the combining nozzle and some of the steam, having no passage of escape, would blow back into the water supply pipe rendering the injector inoperative.

This would occur when ever the injector is subjected to any shock (due to the engine going over points or to the roll of a ship), the. jet being broken so that the whole process of starting has to be gone over again. The instrument is therefore termed "non-restarting."

When the needle is only slightly withdrawn, the area of the jet will be less than the area of the delivery nozzle throat so that it will act as an ejector, air being exhausted from the water supply pipe. Water will therefore be forced up into the injector by atmospheric pressure. Thus the injector will lift its water from a lower level and may therefore be termed a lifting injector. Injectors which do not possess this property are said to be "non-lifting injectors." In this, the original Giffard construction, the cones were solid and not renewable while the steam ram packing could not be relied upon. Therefore, in 1864, a patent was taken out for an improved construction by Mr. Gresham. He dispensed with the steam ram and substituted fixed nozzles, while water regulation was effected by moving the combining nozzle by means of a rack and pinion. The cones could now be removed for cleaning and were renewable.

The first radical improvement appeared in about 1869 when the divergent steam nozzle was introduced into this country, its functions having been discovered by Schau, an early injector maker of Vienna. Its importance will be realised better when the steam nozzle is considered in detail.

PRINCIPLE OF OPERATION.

The injector is an instrument in which a jet of steam moving with high velocity is condensed by a supply of water moving at a low velocity, the momentum of the steam being transferred to the water, producing a combined jet moving with sufficient velocity to overcome the pressure of the boiler.

The Author will endeavour to illustrate the action by taking actual figures from the Transactions of the " Institution of Locomotive Engineers, " where they are to be found in a paper read by Mr. Gresham.

The pressure of the boiler was given as 180lbs. per □″. It is found from steam tables that at this pressure 1lb. will occupy 2.35 cubic feet.

Adiabatic expansion takes place and the steam will fall in pressure and gain in velocity as it passes down the nozzle. What actually happens in this nozzle will be discussed at a later stage and it will be sufficient to state that steam will issue at a pressure of 4lbs. absolute with a velocity of 3,611 feet per second and its volume per lb. will be 74.2 cubic feet.

The area of the jet will now be 6.5 times the minimum area of steam nozzle.

Imagine this stream of steam to be condensed in an ideal combining cone, yet being kept separate from the water effecting condensation.

Its volume will shrink from 74.2 cubic feet to .016 cubic feet.

The area after condensation of net will equal $\frac{\text{final volume}}{\text{original volume}}$ $\times$ 6.5 times the area of steam nozzle, which equals 1/115 of the area of steam nozzle.

It will be noted that the minimum area of the steam nozzle is taken as the unit of area. Thus the jet of water would pass through a delivery nozzle of an area of 1/115 of that of the steam nozzle with a velocity of 3,611 feet per second (two-thirds of a mile per second, 40 miles a minute or 2,400 miles per hour, which is the speed of a rifle bullet). This has to force open a clack valve at 180 per □″. Instead of this pressure imagine a column of water of equivalent height, and knowing that 2.3′ of water are equivalent to 1lb./□″ it will be seen that, as far as the state of affairs at the clack is concerned, the jet has to enter a column 414 feet in height. A jet of water from the valve would have a velocity = $\sqrt{2\,gh}$ where

g = acceleration due to gravity

h = head of water or equivalent

=163.5ft. per second.

this having only 1/23rd of the momentum of the jet of water considered.

Thus it is seen that nearly 22/23 of the momentum of the steam is available for forcing water into the boiler.

The steam on condensing, however, combines with the jet of water usually in the proportion of 13lbs. of water to 1lb. of steam ; thus the volume of the jet is increased 14 times. It has but the same momentum as before but 14 times the mass. Therefore, the velocity is now $\frac{3611}{14}$ feet per second = 258 feet per second.

There is, however, the slight velocity of the water before condensation to take into account, so momentum of steam (1×3611) + momentum of water $(13 \times 40) = 14 \times$ new velocity, because momentum before impact = momentum after impact,

thus final velocity = 295′ per second.

It will be noted that the Author has taken the velocity of water entering the injector to be 40ft. per second. This is because there is a vacuum of 22″ in the injector, so the $\sqrt{2gh}$ formula will give the value of 40′ per second.

Detrimental factors have, however, to be taken into consideration such as friction, eddies and losses due to the molecules of steam not striking the water in the proper direction. These reduce the actual velocity from 295 to 178 feet per second or thereabouts.

Considerable improvement can be made by reducing these impact losses and it has been suggested that a telescopic combining nozzle would effect this.

As its volume has increased 14 times from $\frac{1}{715}$ to $\frac{14}{715}$ of area of steam nozzle the new area becomes $\frac{1}{715} \times 14 \times \frac{3611}{178} = \frac{1}{2.5}$ × area of steam tube. That is the diameter of steam nozzle is to the diameter of delivery throat as 1 is to 1.58, which approximates to general practice.

To obtain the actual amount of water delivered in cubic feet per hour a formula is given

$$Q = 0.374 \quad D^2 \quad \sqrt{P+10}$$

where Q = cubic feet of water

D = diameter of delivery nozzle in millimetres

P = gauge pressure.

The results obtained give a fair resemblance to what is actually obtained up to the limits for which an injector is designed. To suit modern conditions an injector has to be designed to give results under a very varying set of conditions, some variable factors being given below. It will be seen that they form a formidable array. They are :—

1. Density of steam.
2. Pressure and temperature of steam.
3. Dryness fraction of steam.
4. Temperature of feed water.
5. Velocity of feed water.
6. Velocity of incoming steam.
7. Ratio of steam to water.
8. Pressure on boiler being fed.

Having gained a rough idea of what happens in the injector, each nozzle will be examined in detail.

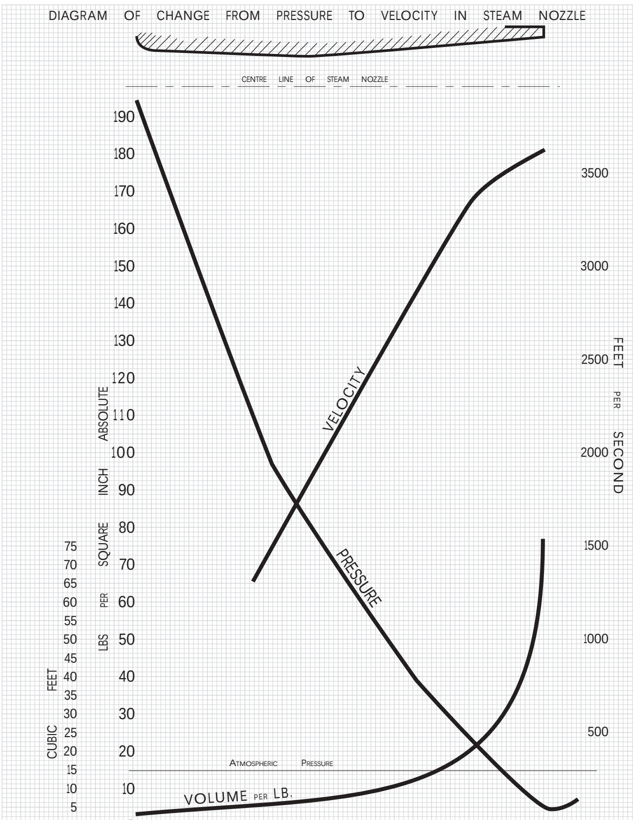


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FIG. 2.

THE STEAM NOZZLE determines the quantity of steam used, directs its flow and gives it the maximum possible velocity. The rate of change from pressure energy and heat energy to velocity energy brought about in the nozzle is represented graphically in Fig. 2.

It will be understood that the same weight of steam will pass each cross section of the nozzle in unit time. Let the nozzle be of such a size that 1lb of steam passes in each second. At 180lbs. per □″ pressure, 1lb of steam will occupy 2.35 cubic feet. Adiabatic expansion will follow and the steam will fall in pressure but gain in velocity.

As velocity increases the area of the nozzle must decrease and as volume per lb. increases the area of nozzle must increase (unit weight passing each section in unit time). Therefore the actual area of cross section depends on the product of these two factors.

This product will be found to decrease until the pressure reaches 0.55 of the initial pressure (so far the nozzle is convergent) after this the product increases so that the jet expands laterally. (Thus the nozzle is made to diverge). This is the diverging nozzle mentioned in connection with Schau.

The steam continues to expand until exhaust pressure has been reached, about 4lbs. absolute (volume per lb =742 cubic feet) giving a velocity of 3,611 feet per second, as previously stated.

$$\text{Thus the area of cross-section} = \frac{\text{Velocity at throat}}{\text{Velocity at end}} \times \frac{\text{Volume per lb. at throat}}{\text{Volume per lb. at end}} = \frac{1407}{3611} \times \frac{742}{441} = 6.5\,\square$$

The steam nozzle is preferably made short than long because if it is long, velocity is lost by the steam trying to fill out too big a cone, whereas if it is short, heat will be given to the surrounding water so that the thermal efficiency will be very little affected.

THE COMBINING CONE receives the steam and water and its function is to ensure as complete a condensation as possible of the steam jet by the water so that maximum energy is transferred with as little loss as possible.

The shape of this cone is convergent, the bore gradually decreasing so as to support and guide the jet throughout the whole of its length ; the jet at the inlet end consists of a mixture of steam and water and at the outlet end consists of a jet of water flowing with high velocity. The internal contour of the jet should conform as much as possible to the varying form of the mixture as condensation takes place, and as no definite rules exist, it will be found that every manufacturer has his own designs, which have been evolved from experiments. Three factors present themselves in this connection. They are:—

(1) The inlet area must provide a guiding and supporting wall for the water as it enters the injector and during the impact of the steam thereon.

(2) Convergence to support varying jet.

(3) The length must be sufficient to ensure complete condensation.

It would appear to be possible to vary the length of the combining nozzle within fairly wide limits without materially affecting the efficiency of the injector. Indeed injectors have been tried with a nozzle of only four times the length of the diameter of the delivery nozzle throat, however greater stability will result in a longer nozzle.

The rate of decrease in the diameter of the nozzle towards its exit is in most injectors uniform, the difference between diameters at any two equidistant sections is the same, giving the nozzle a conical form. In some cases, however, the rate of decrease is more rapid at first as the water will be correspondingly more rapid. Therefore combining nozzles are made with a taper varying from 5° to 15° at the inlet end.

The combining nozzle is subjected to considerable wear if the feed water is anything but pure, so it is sometimes made in two portions. The separate inlet portion being known as the draft tube, the lifting cone or the water nozzle.

If the water contains solid matter in suspension, this is precipitated against the walls of the draft tube by the impact of the water. It pays therefore to have clean water to avoid scouring the nozzle.

The jet, on leaving the combining cone, passes into the delivery cone, crossing a small space known as the overflow-gap which is needed for starting purposes.

THE DELIVERY NOZZLE consists of a parallel portion known as the throat, followed by a diverging cone. The function of this cone is to turn the kinetic energy of the jet into pressure energy with as little loss as possible. When the jet leaves the combining cone it is moving with high velocity, but with very low pressure. This pressure must be increased to overcome that of the boiler.

The easiest way to follow the action of this cone is to imagine it to be divided up into sections of equal volume. Since the cone is a divergent one, the strips will become narrower as the jet proceeds, while the area of cross section will increase.

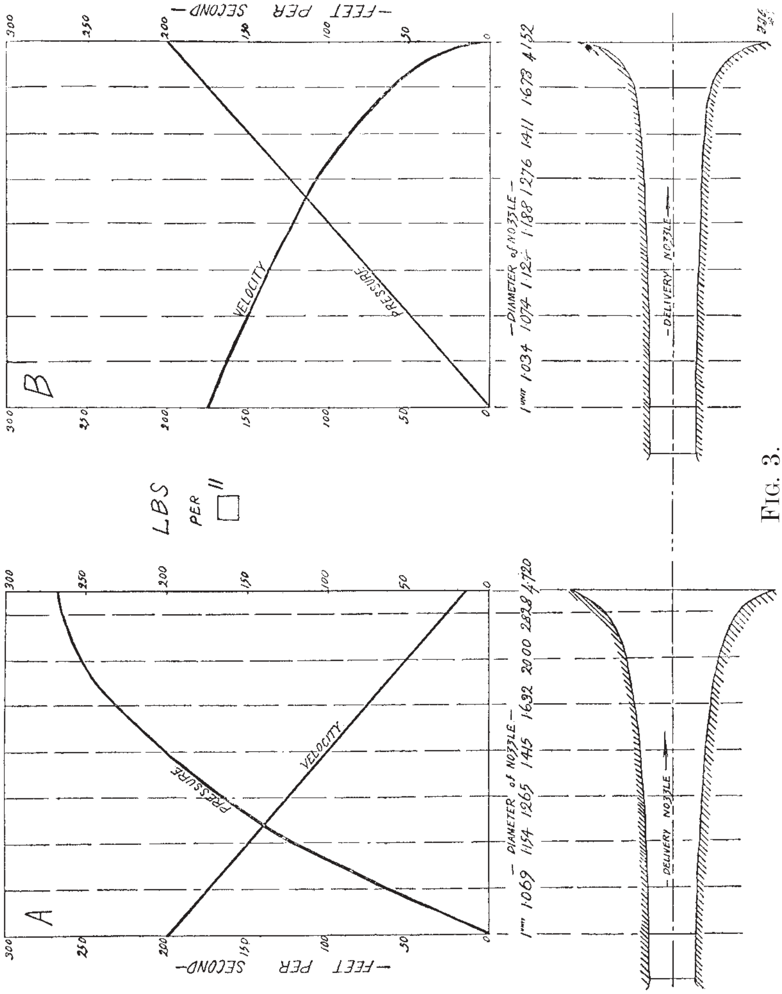

Fig. 3.

Thus as equal weight of water passes each section in unit time, the velocity of the jet will decrease and the pressure on the wall of the cone will increase on proportion (Fig. 3).

In this way the momentum of the jet, which is greatest at the throat, is reduced while the pressure is increased to boiler pressure.

The diverging nozzle has received a large degree of attention, apart from the injectors, on account of the fact that by its aid the quantity of water discharged through an orifice in given time may be increased, provided that the jet is completely able to fill the diverging nozzle.

A highly interesting article on the subject will be found in the number of " Engineering " dated 12th February, 1912, written by Professor A. H. Gibson, D.Sc.

In the injector it will be understood that the delivery nozzle must always be full of water owing to the boiler pressure resisting flow, and if the nozzle be cut at several places as previously mentioned, the same weight of water will pass each section in given time (assuming water density constant) notwithstanding variations in the areas of the respective sections. Therefore the product, velocity × sectional area = a constant.

Then, since area of cross section = πR^2, velocity × d^2 = C thus velocity in ft./sec. at any section =

$$\frac{\text{Volume in cubic feet per second}}{\text{Area of section in } \square'}$$

or since $d_1^2 \ V_1 = d_2^2 \ V_2$ = constant.

$$V_2 = \frac{d_1^2 \ V_1}{d_2^2}$$

Where V_1, V_2 { initial and final } velocities and { d_1 diameter at inlet. d_2 diameter at any section.

Therefore the velocity curve for any predetermined nozzle form may be plotted if the velocity at entrance is known.

If d_1 and V_1 are known,

$$d_2 = \sqrt{\frac{d_1^2 \ V_1}{V_2}}$$ enabling a nozzle to be designed to give

a known velocity curve.

The pressures at any two sections of the diverging nozzle vary with the squares of the velocities thereat, if V_1 and V_2 are known then $\frac{V_1^2 - V_2^2}{2g}$ + the head at section 1 = Head at section 2.

$$H_2 = \frac{V_1^2 - V^2}{2g} + H_1$$

or as head in feet

$$= \frac{\text{Pressure in lbs. per } \square'}{\text{Wb per cubic foot.}}$$

$$\frac{P_2}{W} = \frac{V_1^2 - V^2}{2g} + \frac{P_1}{W}$$

DIAGRAM " A " in Fig 3 shows the diverging portion of the nozzle so proportioned as to cause uniform retardation.

DIAGRAM "B" shows proportion so as to give rise to uniform rise of pressure.

If the form of nozzle be such as to cause sudden increase of pressure where the velocity is high, the jet sets up strong abrasive action and tends to groove the nozzle surface at this point. "B" is then superior to "A" in this respect, but as a nozzle should provide a fairly regular rate of conversion of velocity into pressure so as to produce stability in the jet, "A" has its advantage. In practice a combination of these two forms is sometimes employed.

Other points of design to be noted are :—

(1) The nozzle must not be short, or the quick change of cross-sectional area will set up eddying motions.

(2) The nozzle surface should be as smooth as possible so as not to produce eddying motions in the jet and to offer a minimum of resistance to flow.

It is usual to make the delivery nozzle of cylindrical form at the throat for a distance equal to the diameter of the throat to resist abrasion while, on the Davies and Metcalf injector, the throat is made of "monel metal" which is screwed into the end of the main nozzle.

As has previously been stated, the area of the steam nozzle is 2.5 times that of the smallest diameter of the combining nozzle so that, if for any reason the jet is broken and the supply of water cut off, steam is not condensed and has to pass through a restricted area. As it cannot do this it will blow back down the supply pipe. In the Giffard injector when this occurred the spindle had to be adjusted and the supply of steam reduced until the jet had been "re-started." As a break is likely to occur at any jolt from the road or variation in steam pressure the injector required constant attention. Such an instrument would be hardly suitable for modern locomotive practice when so much of the fireman's attention is required for other purposes. An automatic restarting injector is therefore called for which will provide, by means of some auxiliary overflow arrangement, a free and full discharge of excess steam from the steam nozzle to atmosphere, until condensation has been resumed.

Under normal conditions the pressure in the large end of the combining nozzle is below that of the atmosphere, because condensation is taking place, so that it must be sealed to prevent the entrance of air.

In an injector of White's Limited the combining nozzle is made in two portions the intervening gap giving access to a chamber which communicates to the atmosphere, giving a discharge for the excess steam. When the injector is working, however, the pressure in this part of the cone is replaced by a vacuum due to the condensation and the spring loaded valve closes, preventing the entrance of air. The overflow gap proper is not sealed as the internal pressure of the jet at this point is atmospheric.

G.W.R. RESTARTING (Fig. 4). In this injector a free passage is given to the superfluous steam by means of a flap nozzle. The combining nozzle is split for part of the way in a horizontal direction and the detached part is hinged at one end. The two parts are faced and scraped up so that air does not leak through the joints when the flap portion is on its seat. Steam, when there is no water to condense it, lifts this flap from its seat and escapes. On condensation taking place, its weight causes it to fall back on to its seat to support the jet.

When an injector is operating it is apt to draw in air through the overflow pipe owing to the ejector-like action of the jet crossing the overflow gap. As all engineers will know, the admission

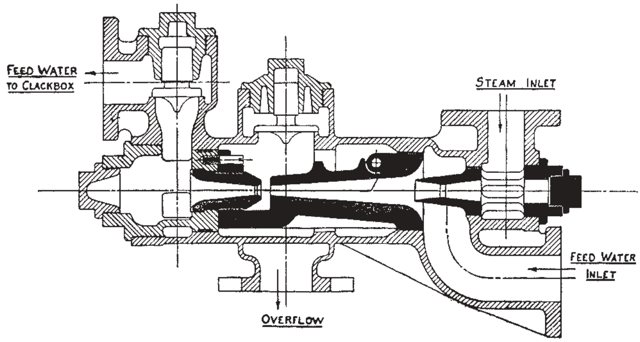

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FIG. 4.

of air is injurious to the boiler, so a valve is provided on the overflow to prevent the admission of an air jet and to give free escape for the overflow steam and water.

A few notes on the construction of this injector may not be out of place. The body is cast and is machined in one setting on a " Kearns " universal boring machine which bores, faces and taps the required portions. The hole is cored out to clear the flap nozzle but boring is necessary in five places. The seven faces are milled, four flanges are ringed, and the water, steam and delivery flanges have four holes drilled in each by multiple drill-heads fixed in the main spindle of the machine. This ensures that the injectors will be interchangeable. The overflow pipe is fixed by two bolts which fit into slots in the flange which are cored in the foundry. The steam nozzle screws into a hole, and is held in position by a steam ram which is also screwed into the body.

The delivery ram is screwed in at the other end of the body and is responsible for securing the two remaining nozzles. This ram fits into a machined hole in the partition between the overflow and delivery chambers and the leaking of water from one to the other is prevented by cord packing. The delivery nozzle fits into this ram but is not secured directly. It is, however, screwed into a projection of the combining nozzle which is prevented from rotating by a dowel which is placed in such a position that the flap will always rise vertically. The steam end of the combining cone fits into a corresponding machined portion of the body and is kept steam tight by appropriate packing. Plugs are provided at each end for inspection and to give access to the spanners which withdraw the cones. The steam nozzle is provided with a hexagon to fit a box spanner, while the delivery nozzle is slotted to provide a grip for a screw driver to withdraw the delivery nozzle. It will be seen that all the nozzles are easily withdrawn for cleaning.

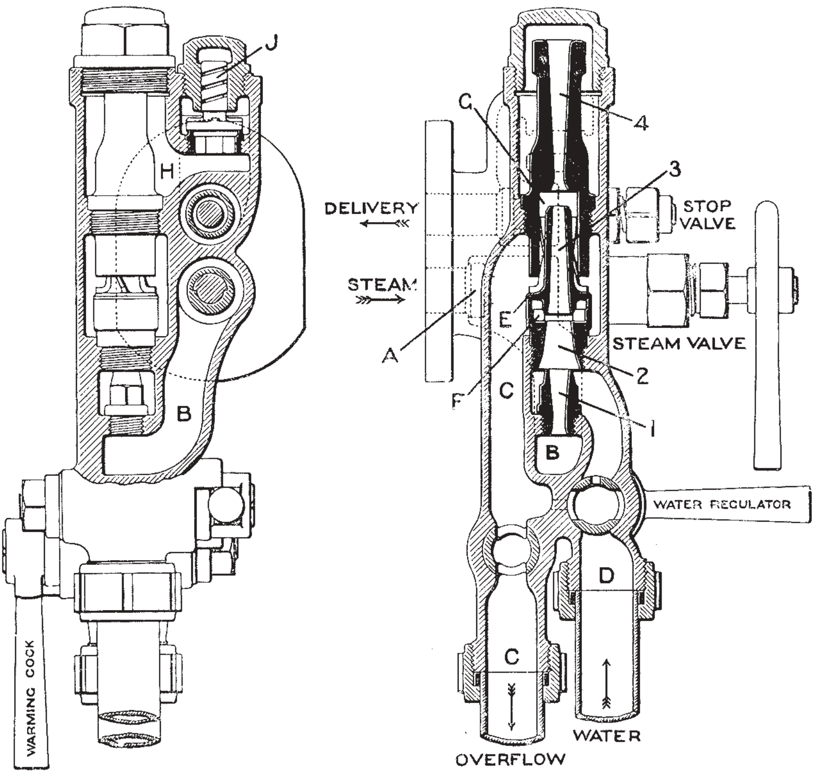

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FIG. 5.

To remove scale the nozzles should be immersed in a solution of one part muratic acid to 10 parts water.

THE COMBINATION INJECTOR (Fig. 5) is so called because all the necessary valves and fittings are placed on one casting. This injector is arranged vertically and to make it automatic, a sliding cone (3) is provided which rests on a seat (E) provided by a cylindrical extension of the draft tube. When steam is in excess, as on starting, it lifts the cone bodily allowing escape to overflow. Its movement is confined by the cylindrical extension of the combining cone. On condensation taking place the nozzle falls on to its seat forming an effective seal to the entrance of air.

The cock is provided in the overflow tail pipe so that, when it is closed, steam may be made to blow through to the tender, thus saving steam which might go through the safety valve when the locomotive is standing, as well as providing what is, in effect, a feed water heater. The passages on this instrument are so arranged that it may be mounted direct on the back of the fire-box.

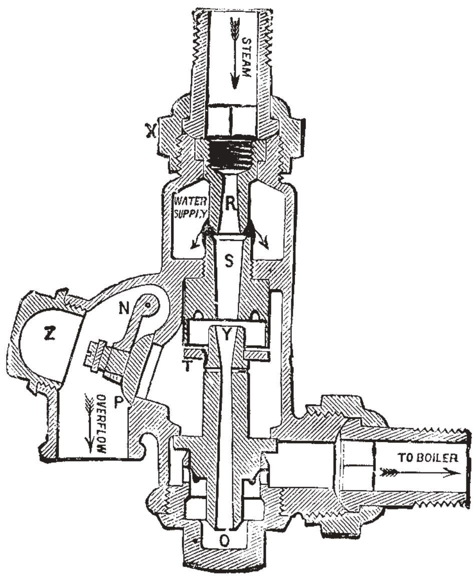

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FIG. 6.

THE "PENBERTHY" INJECTOR is illustrated in Fig 6. The outstanding feature of this design is the method of sealing the aperture provided for the egress of steam from the combining cone on starting. A series of holes are drilled in the combining cone to allow the escape of steam. These communicate with a cylindrical chamber which surrounds the cone, sealed at one end by junction with the cone and open at the other end to overflow. A ring is provided which rests on a ledge on the combining tube and forms an air tight fit around it. On normal working taking place a vacuum is created in the annular chamber which lifts the ring which is held against a face on the cylindrical portion by atmospheric pressure. The chamber is thus effectively sealed from the ingress of air. An overflow valve is provided.

THE " SELLARS " RESTARTING INJECTOR is another of American origin with similar characteristics. Steam enters, discharging through a draft tube into the overflow chamber, thence to air, lifting water to the injector. The partial vacuum formed by condensation of the steam lifts a bushing up against the draft tube preventing the admission of air.

Another bushing will also fall on to a seat on the delivery cone preventing any "ejector" like action at the overflow gap.

On the jet being broken the first bushing will fall and the second bushing will be forced off its seat by steam pressure allowing free escape for excess steam.

For an injector to function properly (i.e. with maximum delivery and minimum overflow) the exact amount of water must be admitted to condense the steam entirely, an excess resulting in overflow and deficiency, in reduced lift and delivery. As the amount of water required varies with the pressure of the steam supplied, it will be apparent that some regulation of water supply will be necessary if the pressure is likely to vary over an appreciable range.

In the " WHITE'S OWN RAPID " injector regulation of steam supply is effected by moving a handle to a mark on the pointer corresponding to the gauge pressure in the boiler supplying steam. This handle drives a cam which raises and lowers the steam spindle altering the effective area of jet by the conical tip of the spindle working up and down in the mouth of the steam cone.

This injector is fitted with a flap nozzle, similar to the one illustrated under the head of the G.W.R. injector, to provide for automatic restarting.

Another injector is on a similar principle and is called the " ACME. " It has a needle effecting regulation moved up and down by the spindle, which is screwed and fits into a fixed nut. An indicating scale is fixed on the body of the injector over which passes a pointer which is an extension of the handle fitted to the rotating spindle. Automatic restarting is ensured by a sliding cone as in the combination injector previously described.

In another injector, the " SIRIUS " (Fig. 7), the water and steam volumes are varied simultaneously by the movement of one handle. This handle, which has a pointer as before, does not move vertically but the spindle is screwed into a nut which is prevented from rotating but lifts the steam nozzle bodily when the handle is turned. This alters the distance between the bottom of the steam nozzle and the top of the combining nozzle thus varying the water supply, while the bottom of the spindle being pointed reduces or increases the effective area of the steam jet as the nozzle is raised or lowered. It is made automatic restarting by a valve and chamber as patented by Whites Limited and as previously described.

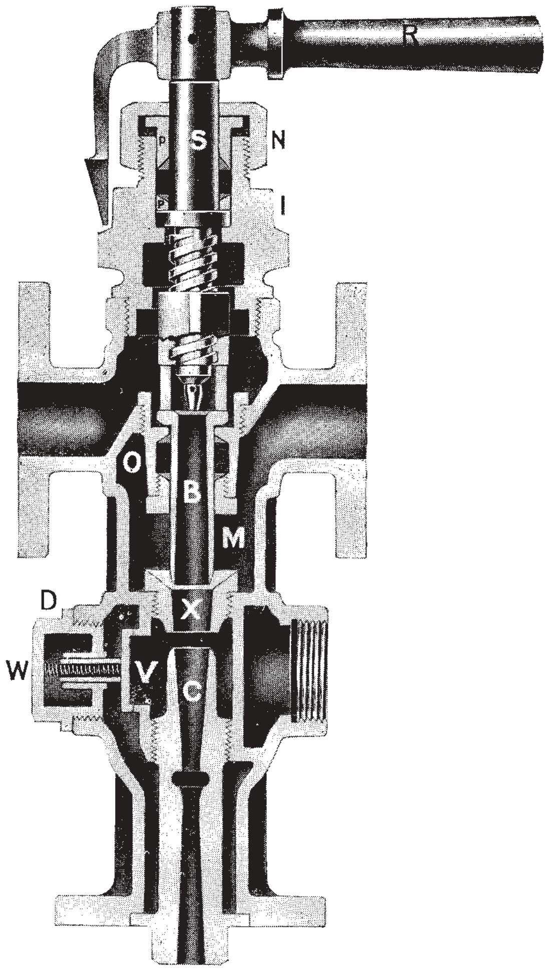

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FIG. 7.

THE BUFFALO " B " is an injector of the ordinary restarting type, wherein water and steam are regulated simultaneously.

By turning the handle the steam nozzle is drawn back together with the water valve. Steam is first admitted via the hole in the side of the cone, and then by the end. Holes are provided in the combining cone to allow excess steam to escape. The overflow valve is relied upon to prevent the entrance of air.

In America and on the Continent the development of the injector took place on slightly different lines.

Giffard, realising the necessity of making the injector automatic, suggested a method by which this could be done. His idea, which was followed by Sellar's in America and Korting and Friedman in Hanover, was to subdivide the functions of the steam jet by providing one jet for lifting the water and supplying it under pressure to the nozzle. Such cones may either be placed concentrically or eccentrically and two examples will suffice to illustrate this.

THE SELLARS " K " INJECTOR (Fig. 8). On starting the handle is pulled back slightly, which, acting through the crosshead (8) slightly withdraws the spindle permitting steam to enter the annular nozzle. This steam, rushing through the nozzle known as the draft nozzle, causes an ejector action to take place exhausting air from the feed pipe (23). Water is therefore forced up the pipe by atmospheric pressure and enters the combining cone. The spindle is then withdrawn fully, allowing steam to enter the main nozzle (3). Should the jet be broken by any shock

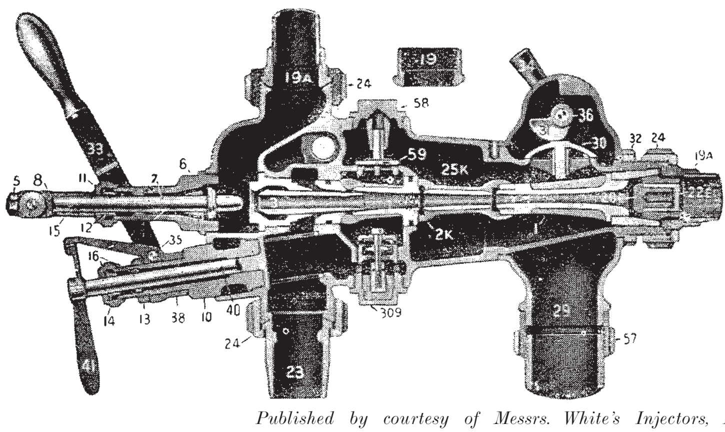

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FIG. 8.

from the road, condensation does not take place and the excess steam escapes by the openings in the combining nozzle until normal working is resumed. The entrance of air is prevented by valves (59 and 30). The spring loaded valve (309) is provided so that, when the injector is working normally, water will be drawn into the overflow chamber and a certain quantity is picked up at the overflow gap and sent on into the boiler. This feature renders the injector self adjusting. The cam (36) closes the clack at the overflow for hot water working as will be explained later. Hot water working with this injector therefore locks the overflow rendering restarting impossible.

THE BUFFALO "A" DOUBLE TUBE MACHINE (Fig. 9) is an example of eccentrically placed nozzles. It has two sets of jets, the lower set lifting the water and supplying it under pressure to the upper set.

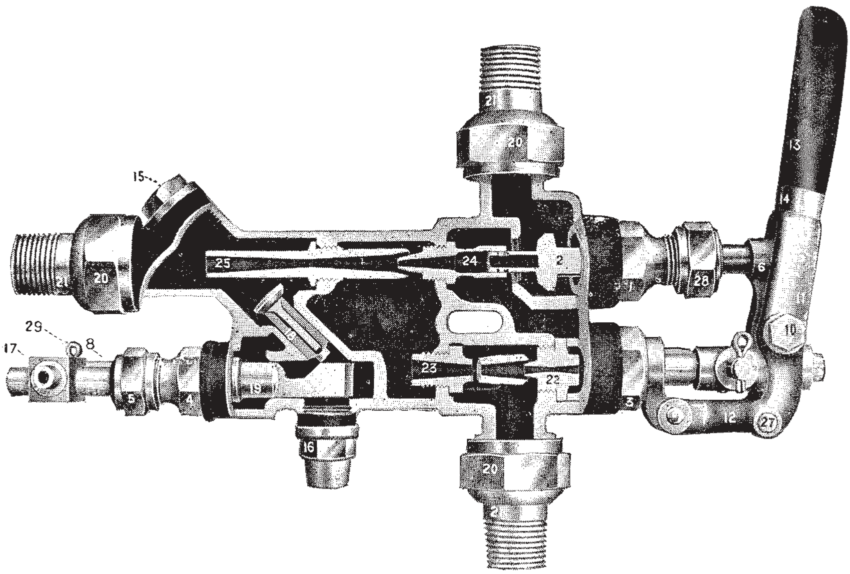

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FIG. 9.

To start the injector the handle is pulled out slightly allowing steam to pass around the spindle (2) to the lower steam jet (22) but not through the upper jet (24). The water then rises in the suction pipe and is passed through jet (23) and out to waste through the overflow valve (18) and out past the spindle (19). The handle is then pulled out as far as it will go, steam being admitted to the main steam nozzle. This establishes the feed. A link connects the handle with crosshead (17) so that, simultaneously with the final movement of the handle, the spindle advances allowing the overflow valve (18) to fall on to its seat.

HOT WATER INJECTORS.

It has been seen that the action of the injector depends upon the condensation of the steam by water. If then, the water is fed to the injector in a heated condition condensation will not be effected so readily and to lift hot water an injector has to be specially proportioned.

Besides the slight alteration of the proportion of the nozzles to lift hot water, provision has to be made to close positively the overflow gap, as mentioned when the function of the cam in the double tube "Sellers" machine was explained. This is necessary, as will be understood when it is realised that the temperature of the jet resulting from the combination of steam at 180lbs./□″ (380° F.) and feed water at 140° F. is between 240° F. and 250° F. Water at this temperature if exposed to atmosphere pressure would boil off when passing the overflow gap and never enter the boiler at all.

The hotter the feed water the less steam will it be capable of condensing so that the density of the final mixture will be considerably reduced. To make up for this loss of density the weight of water per lb. of steam is reduced, thus increasing the velocity. Thus sufficient momentum is gained to feed the boiler.

Consider a numerical example :—

Cold water. Boiler pressure 160lbs. / □″, 60° F. feed water —velocity of jet 140′ /sec.

Hot water. Boiler pressure 160lbs. / □″, 140° F. feed water —velocity of jet $155\frac{1}{4}$′ /sec.

Momentum of jet.

140′ /sec. × 15lbs. of water at 60° F. =2,100ft. lbs./sec.

155.25′ /sec. × 11lbs. of water at 60° F. = 2,098ft. lbs./sec.
a difference of only 2ft. lbs./sec.

Apart from the nozzle proportions then, the essential distinctive feature of a hot water injector is the provision for the positive closing of the overflow valve against pressure acting from inside. This is usually accomplished by utilising the pressure of delivery, which, of course does not exist when the injector is starting or when the jet breaks.

It does not give satisfaction however when the delivery pressure is allowed to act directly on the valve as every minute fluctuation in pressure would result in the opening or closing of the valve, which should remain open until the full jet is established and should remain firmly closed when the injector is operated normally.

The arrangement will be more clearly followed on consideration of the following types of injectors :—

THE GRESHAM & CRAVEN HOT WATER INJECTOR is supplied in both the combination and non lifting forms. The non lifting pattern has the combining cone in two portions, the intervening space communicating to a chamber closed by a flap. The overflow pipe is also fitted with a clack to prevent the admission of air. The delivery cone is not rigidly fixed but slides in a closely fitting guide which is fitted with a stuffing box to make it quite watertight. When this sliding cone is back as far as it will go it beds into a seat provided on the combining cone, making a steam tight joint.

On starting, the steam and water force the cone away from its seat and escape through the overflow but when condensation fully takes place the jet passes on through the cone and, as it acquires a pressure which acts on the cone, the latter is forced back into its seat preventing the jet from breaking into steam at the overflow gap.

The combination pattern acts on the same principle, is arranged vertically and can lift its feed water.

DAVIES & METCALF'S HOT WATER INJECTOR. The combining nozzle of this injector is divided into two separate parts, the first or supplementary chamber communicating with the overflow pipe by means of an ordinary hanging type valve ; the second, or main chamber, being fitted with the pressure controlled overflow valve.

The portion of the combining nozzle in the first chamber is provided with a gap or slot situated between the ends of the two steam nozzles, while that portion in the main chamber is constructed on the flap nozzle principle as described in connection with the G.W.R. injector. In starting or restarting the injector the steam from the lifting nozzle escapes through the gap, while the steam from the central forcing nozzle escapes through the overflow valve into the overflow pipe. Fig. 10 shows the combination pattern.

The automatic valve consists of the overflow valve (Fig. 11) which seals the overflow chamber and a small piston which is fitted into the delivery chamber of the injector. The piston is coupled to a lever pivoted on a fulcrum on the injector casing, the other end of the lever bearing against the upper stem of the overflow valve.

When the injector jet breaks off from any cause, the delivery pressure under the piston is reduced and the valve opens, allowing overflow to take place until delivery pressure again acts. A spring is provided under the valve end of the lever to resist any slight pressure that may exist in the delivery cone before a proper jet be formed, thus preventing premature closing of the overflow valve.

A further feature of the injector is the supplementary water passage, connecting the water pipe with the first overflow chamber. It is found that at the gap in the lower part of the combining

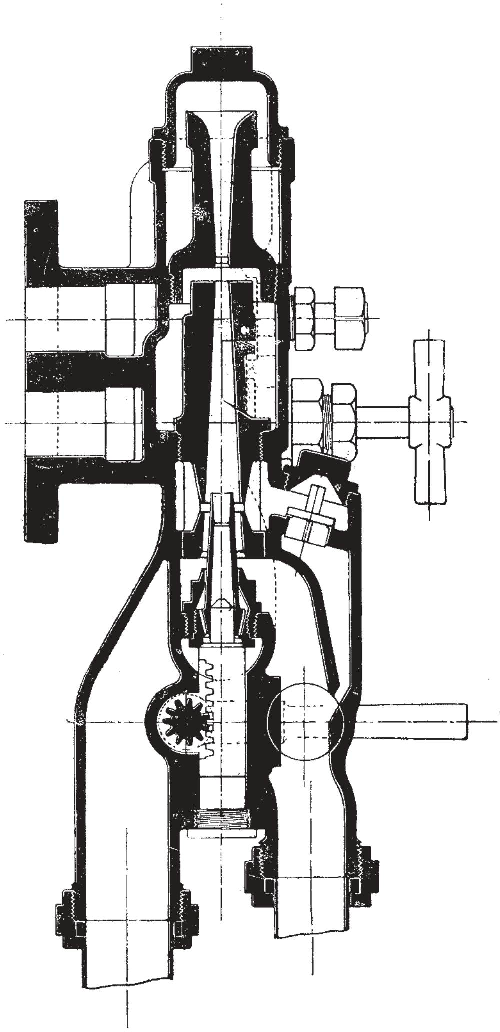

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FIG. 10.

nozzle a considerable vacuum is formed and this is utilised to draw in an additional supply of water, so increasing the delivery of the injector and strengthening the jet. A non-return valve is fitted into the passage to prevent any steam blowing back into the supply pipe.

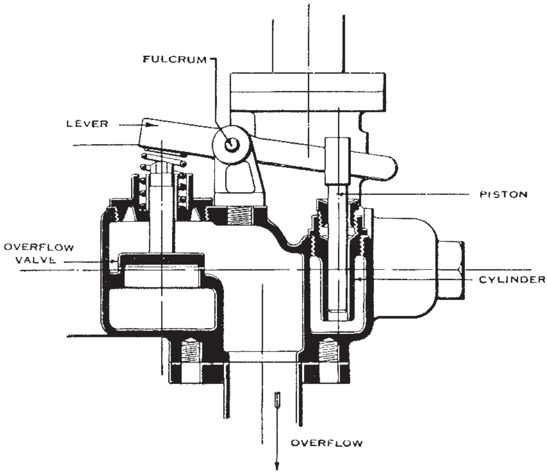

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FIG. 11.

THE " PENBERTHY " AUTO-POSITIVE. This injector has a series of holes drilled in the combining cone communicating with the overflow chamber which is sealed by means of a clack valve. Pressure in the delivery chamber acts on the back of the pressure valve, which is forced out until it meets the overflow valve which it forces against its seat. When the injector is starting, steam and water are at liberty to escape by way of the overflow valve but, on a jet being established, delivery pressure forces out the valve which closes the clack against any pressure which may prevail in the injector due to the jet of hot water breaking into steam as it crosses the overflow gap.

HOLDEN & BROOKE'S " SUPER-JET " INJECTOR resembles in appearance an ordinary restarting injector but has the overflow gap closed by the action of delivery pressure in moving the delivery nozzle against a seat.

To prevent the premature closing of the overflow by slight pressure, before the jet is properly formed, steam pressure is allowed to act on the inboard side of the delivery nozzle ; steam flowing from steam nozzle to the chamber where it acts on the delivery nozzle. This nozzle is thus held away from the face until delivery pressure, having a larger effective area on which to act, forces it back on to its seat. When there is no jet the combining nozzle may move to provide for automatic restarting.

In devising the injector Giffard was seeking a light, compact boiler feeder for his aviation experiments and probably he did not realise he was producing an instrument which was almost thermally perfect and would become an almost universal fitting.

As a pump the injector is not very efficient as will be seen when it is realised that the mechanical efficiency expressed in heat units, represented by

$$\frac{\text{Heat Units Used In Doing Work.}}{\text{Heat Units Available.}}$$

is equal to about 3% ; but when it is remembered that it also acts as a feed water heater and all the heat not used in lifting and forcing water into the boiler is returned to the boiler in the form of hot water its efficiency will be realised.

Thus the injector performs the double duty of force pump and feed water heater and as such is almost thermally perfect, the only loss being due to radiation. A pump, when compared with an injector, is at a disadvantage owing to its heavy construction and mechanical complication and to the fact that it gives off all its exhaust steam to the atmosphere so losing its latent heat.

Compare the respective coal consumptions of a boiler fitted with an injector and one fed by a pump. Take the evaporation capacity of the boiler to be 10lbs. of water per lb. of coal from and at 212° F. The working pressure is 160lbs. and the temperature of water in the tender is 63° F.

The actual evaporation $\frac{966 \times 10}{1226 - 180}$ =9.28lbs. of water

where 966 = latent heat of 1lb. of water at 212° F. and 1,226 = the total heat of 1lb. steam at 160lb./□″ and 180° F. the temperature of feed water after passing through injector.

On a boiler fitted with a pump the actual evaporation will be $\frac{966 \times 10}{1226 - 63}$ = 8.25lbs. of water/lb. of coal.

Therefore coal required to evaporate 18,000lbs. of steam per hour $\frac{18{,}000}{9.28}$ = 1,940lbs. of coal using injector and $\frac{18{,}000}{8.25}$ = 2,180lbs. of coal using pump.

The power required to force 300lbs. of water per minute into the boiler $\frac{160 \times 2.38 \times 300}{33{,}000}$ = 3.46h.p. where 2.38 is the equivalent head in feet per lb. / □″

Since 1 h.p. is equivalent to 42.41 B.T.U. per minute, coal actually used to feed boiler $\frac{42.41 \times 3.46 \times 60}{13{,}600 \times \text{Boiler Efficiency}}$ where 13,600 is the calorific value of the coal = .91lbs. per hour.

Coal used in heating feed water $\frac{18{,}000 \times (180-63)}{13{,}600 \times \frac{70}{100}} = 2{,}065$lbs per hour.

For a pump the coal required will equal

$$\frac{3.46 \times 100 \times 42.41 \times 60 \times 3}{\frac{71}{100} \times 13{,}600} = 2.7\text{lbs.}$$

<u>Fuel used per hour in injector fed boiler.</u>

Coal used in evaporation		1,940 lbs.
Coal equivalent in injector	feeding	0.91lbs.
	heating	206.0 lbs.
Total coal used		2,146.91lbs.

<u>Fuel used per hour in pump fed boiler.</u>

Coal used for evaporation	=	2,180 lbs.
Coal used in pump	=	2.7 lbs.
		2,182.7lbs.

Coal saved by using injector = 35.80lbs.

A further advantage of feeding by injector is that many strains in the boiler due to the uneven temperature may be eliminated.

Desirable as these savings may appear the large amount of steam demanded by the injector provides a constant tax on the boiler capacity and one will realise the advantage of being able to use exhaust steam to do this work, retaining the live steam injector for use when the engine is standing or coasting, thus using and saving steam which would otherwise go through the safety valve.

When it is remembered that one of the British railways spends as much as £5,929,000 on coal and that a reduction of $\frac{3}{4}$lb per engine mile effects a saving of £92,000 per annum, the value of an injector capable of utilising exhaust steam will be realised, as the heat that would otherwise go out of the blast pipe can be put back into the boiler.

The first step in this direction was to provide a pipe from the blast pipe or exhaust chamber to the injector overflow chamber. In this arrangement the ejector-like action of the jet as it crossed the overflow gap drew in exhaust steam providing a higher degree of feed water heating to the extent of about 12° F.

Although the method was extremely simple the economy attained was not great and attention was directed to the use of exhaust steam as the motive power ; such a machine being constructed in 1876. No real success was attained, however, until the invention of the split combining nozzle in 1877 which opened the way to the production of a practical instrument.

It may appear rather surprising that the exhaust steam at the atmospheric pressure is able to force water into the boiler against the prevailing pressure. It contains energy, however, in the form of heat and when passed through a nozzle, being expanded from a higher to a lower pressure, heat energy is liberated which does work on the steam, giving it increased velocity. As steam at atmospheric pressure has little velocity relative to atmosphere, the whole working of this injector depends on the degree of vacuum attained by condensation of the steam. The following figures may be of interest :—

Vacuum, inches of Mercury.	Velocity, feet per second.
22	2,100
24	2,300
26	2,550
28	2,900

A vacuum of about 28 inches is found at the point of contact of the steam and water so that the velocity of the steam will approach 8,500ft./sec., which it will be remembered is sufficient to operate the injector.

Messrs. Davies & Metcalfe have been engaged for years in the evolution of the exhaust steam injector. They first produced the " A " type which was similar in construction to an automatic restarting non-lifting injector with the exception of the nozzle proportions. Water regulation was effected by moving the exhaust steam nozzle lengthways in the injector body. This injector could feed against a boiler pressure of 75lbs./ □″ and with a supplementary live steam nozzle placed concentrically inside the exhaust steam nozzle it could feed against 150lbs./ □″

For higher pressure the "B" type compound injector was developed. This consisted of an ordinary exhaust steam injector (type "A") feeding into a second live steam injector which augmented the delivery pressure to the desired extent. This injector gave satisfactory economies and many are still in use but the complication of having two injectors in tandem was a disadvantage.

In the "F" type greater efficiency is attained by the admission of exhaust steam in stages and a greater delivery pressure results. This is probably due to the higher degree of vacuum being formed at the condensation area, resulting in a higher velocity, and to the reduction of impact losses where the steam and water combine.

The complete equipment of the exhaust injector includes some suitable connection to the blast pipe or exhaust chamber, a grease separator, steam control valves and piping.

The grease separator is necessary to prevent cylinder oils from being carried into the boiler by the exhaust steam. It is generally known that the presence of oil in steam boilers is apt to cause pitting.

In earlier types a rectangular separator was used in which steam was strained through a cylindrical piece of wire gauze covered with towelling, oil collecting at the bottom of the casing whence it was expelled by means of an automatic drip valve.

This type has been superseded by a separator based upon centrifugal action (Fig. 12). This consists of a spherical casing

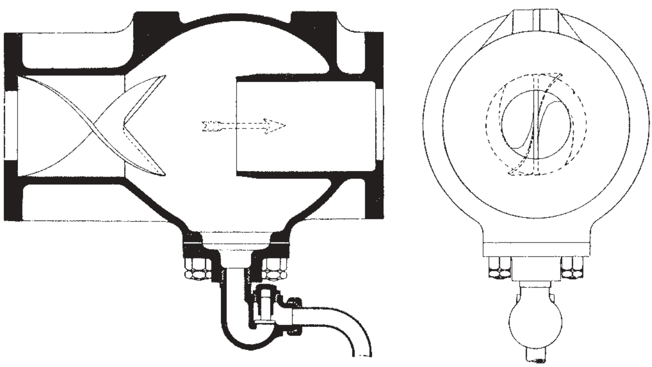

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FIG. 12.

and steam on entering has a whirl imparted to it by means of vanes. As the steam whirls, all the oil and grease are thrown outwards to the sides of the casting whence they are removed by the drip valve ; the steam is drawn off from the centre of the separator in a clean condition.

The injector body itself consists of two castings bolted together and containing the various cones, valves, etc. After having received the supplementary live steam the exhaust steam from the cylinders passes through the central steam nozzle, at the mouth of which it meets the feed water, the combined jet flowing through the draft tube into the vacuum tube. Here the second jet of exhaust steam enters in the form of an annular jet which, combining with the already moving jet. increases its velocity before it enters the combining nozzle, which is of the flap construction. Leaving the combining cone, the jet passes through the delivery cone to the boiler.

The inlet end of the delivery tube is subject to more abrasion than any other part of the injector, and to reduce maintenance costs this portion is made separate and is of a specially hard material and is screwed into the end of the main delivery nozzle.

The admission of exhaust steam to the injector is accomplished by means of the exhaust steam valve which consists of a circular valve hinged at the top. This can be closed by a cam so as to prevent any admission of exhaust steam to the injector. The cam is fixed on a spindle, to which is coupled a rod carried up to the footplate. A refinement consists of a small steam cylinder mounted on the back section of the injector casting and driving

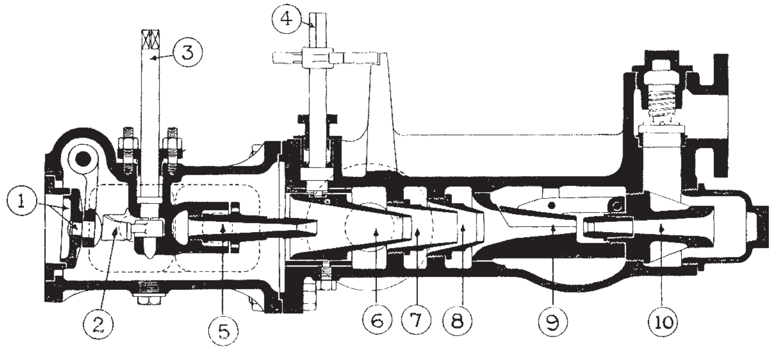

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FIG. 13.

on to a crank on the valve spindle. This cylinder is in connection with the supplementary steam pipe so that immediately supplementary steam is turned on the plunger is forced out, operating the spindle and opening the exhaust valve. The auxiliary live steam is used when the engine is coasting or standing and there is no exhaust steam available. It is admitted to the exhaust steam chamber of the injector and throttled down to atmospheric pressure.

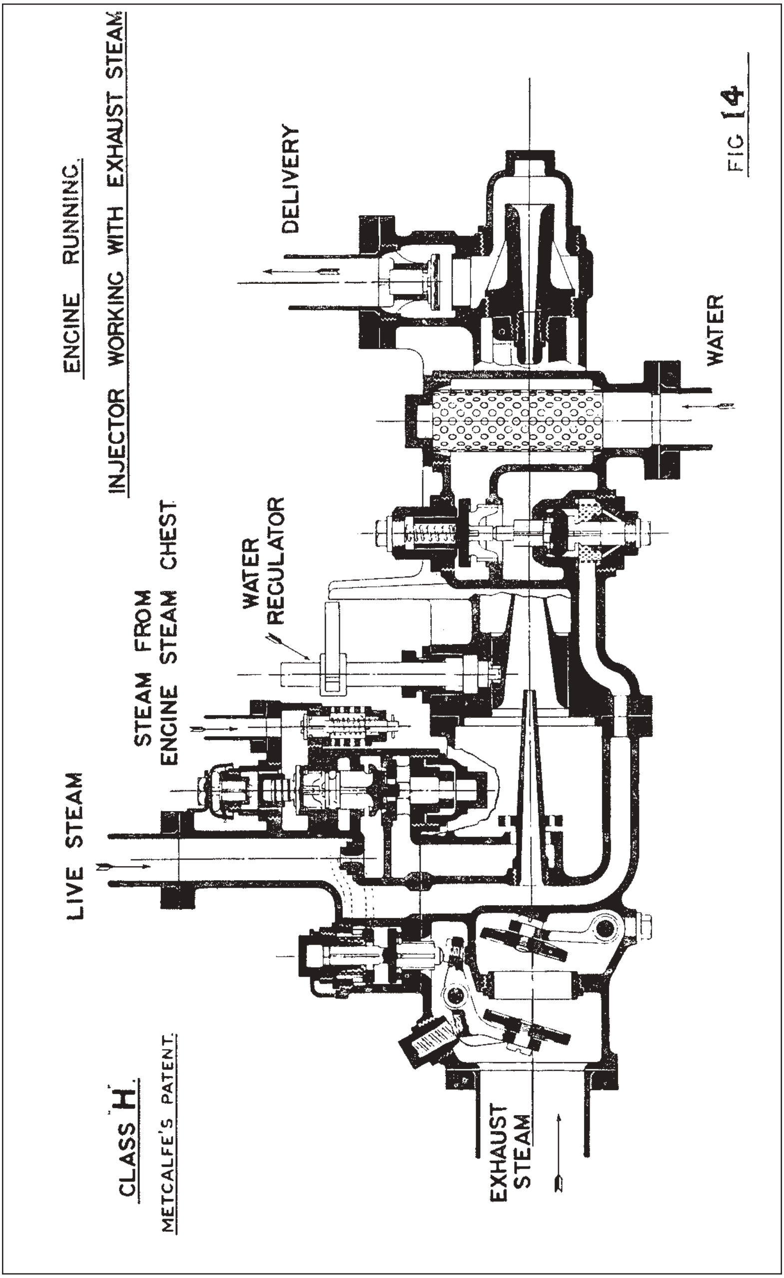
ENGINE RUNNING.
INJECTOR WORKING WITH EXHAUST STEAM
CLASS "H".
METCALFE'S PATENT.
LIVE STEAM
STEAM FROM ENGINE STEAM CHEST
WATER REGULATOR
DELIVERY
WATER
EXHAUST STEAM

FIG 14

As previously mentioned, water regulation is effected by moving the steam nozzle so that the surrounding area between its mouth and the draft tube is varied, thus altering the area of the passage through which the water flows. Deliveries may be so controlled that the minimum is 50% of the maximum. The moving of this cone is effected by means of a rod controlled by a handle in the cab and terminating in an eccentric pin which fits into a steel die which slides in a slot in the outside of the exhaust steam nozzle. Thus on the driver moving the handle the nozzle is moved longitudinally in the body.

A loaded overflow valve is fitted as described previously in connection with the Davies & Metcalfe Hot Water Injector.

The latest type, the "H" type (Fig. 14), has, as its distinctive feature, purely automatic functioning. There are only two controls, the steam valve which is turned on when the engine leaves the shed and is turned off at the end of the day or when the injector is not required, and the water regulator. The change over from exhaust to live steam is purely automatic and is accomplished by means of an automatic valve worked by the steam pressure in the steam chest.

The exhaust valve is steam operated and is of the disc type closing in the direction of the steam. When steam acts upon this piston the valve is held open and exhaust steam is allowed to enter the injector. Another disc valve is freely suspended on the inside face and acts as a non-return valve which offers no resistance to the passage of exhaust steam.

The main feature is, however, the automatic check and shuttle valve (Fig- 15) which controls the automatic action of the injector. In consists of a double sealed valve and operating piston controlling the flow of auxiliary steam from chamber " D." The shuttle piston is operated by steam from the engine steam pipe so that when there is no exhaust steam (i.e. no live steam in engine supply pipe) the valve rises, admitting steam to the chamber " C " and to the auxiliary nozzle. At the same time the upper face cuts off supply from chamber " P " so that no steam flows to hold open the exhaust steam valve which consequently closes.

The steam is thus supplied to the injector through the auxiliary nozzle whenever the regulator is closed to take the place of the exhaust steam which of course does not then exist.

When the regulator is again opened steam passes along the small pipe from the main steam pipe of the engine and acts on the piston of the shuttle valve forcing the latter on to its lower seat, shutting off auxiliary steam arid permitting steam to operate the exhaust steam valve, permitting the exhaust to enter the injector, Thus it is seen that the whole change over from exhaust to live steam and the reverse is purely automatic, relieving the fireman of considerable responsibility.

An anti vacuum valve is fitted in the chamber "E" to prevent any chattering and consequent wear on the check and shuttle valves when the engine is drifting.

Water is admitted to the injector directly steam is turned on by means of a water inlet valve which consists of a clack which is held off its seat by a steam operated plunger when steam is turned on. When steam is turned off the valve falls on to its seat preventing indefinite waste at the overflow. A strainer is incorporated.

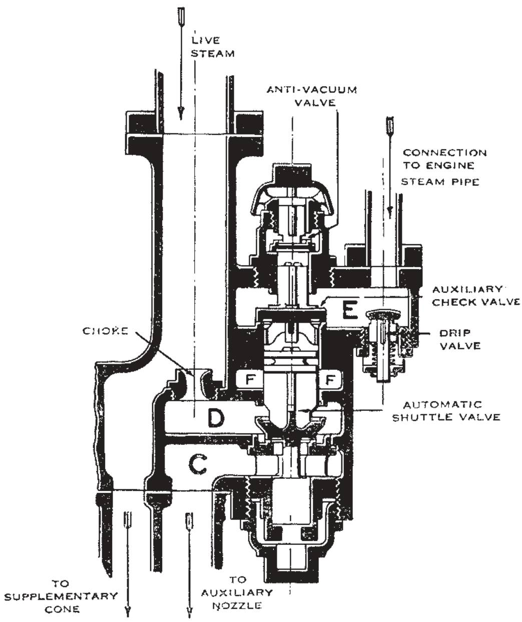

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FIG. 15.

To feed against higher pressures than are usually overcome with exhaust steam, a small quantity of live steam is admitted by means of the supplementary live steam cone which is placed concentrically with the main exhaust steam nozzle. The weight of live steam so used usually amounts to about $2\frac{1}{2}\%$ of the water delivered. This results in no thermal loss as the live steam is condensed by the water, the heat being thus returned to the boiler.

The advantages of the exhaust steam injector may be enumerated as follows :—

(1) Coal economy resulting from use of exhaust steam.
(2) Water economy resulting from use of exhaust steam.
(3) Reduction of cylinder back pressure.
(4) Does not tax boiler when engine is working hard.
(5) Advantages resulting from hot feed.
(6) Compactness and lightness (as compared with other feed water heaters and pumps).
(7) Low initial cost and ease of maintenance.

DISCUSSION.

Mr. W. F. G. Aldridge surmised that there would be difficulty in getting exhaust steam into the injector without the aid of live steam. This, acting more or less as an ejector, would draw in the exhaust steam. There was a tendency for the exhaust steam to rush up through the chimney and it would be necessary for the live steam jet to draw exhaust steam into the injector.

With regard to weather conditions he thought it a well-known fact that restarting injectors gave very little trouble in frosty weather, but in hot weather they presented difficulties.

The Author did not agree that there was that necessity for live steam because the injector could work against 175lbs. sq. in. pressure without the aid of live steam. Mr. Aldridge would find injectors working in the Central Boiler Station which were given no live steam. He agreed that a vacuum was necessary to give the exhaust steam the requisite velocity, but that vacuum was provided by means of the condensation. No doubt live steam did definitely help to create a vacuum, but it was not essential. There would always be a certain amount of pressure (about 4lbs. sq. in.) due to the restricted area of the blast pipe top, so that pressure was available to force enough exhaust steam along to start condensation.

With regard to weather conditions the Author said that he had noticed that one firm recommended hot water injectors for all engines working in hot climates. When the water in the tank became heated it would not condense steam so readily as when cold, and when heated to a considerable degree it would be difficult to lift.

Mr. A. G. Ellis asked what actually caused the wear on the cones of the ordinary restarting injector. The delivery cone was worn very badly just inside the throat.

The AUTHOR in reply stated that water entering at great velocity would tend towards abrasion. With some designs of nozzle the change of velocity was very rapid, and that was apt to cause any particles in suspension to be thrown out against the side of the cone, thus scouring the nozzle. The longer the delivery nozzle the less the abrasion was a general rule. He had noticed that on an experimental injector the nozzle was nearly twice as long as the standard pattern, and he presumed that would help to reduce the abrasion.

Mr. J. A. BREWER understood that the high pressure locomotive recently constructed by the L. & N.E. Railway was fitted with injectors. He asked for information regarding the boiler feeding arrangements of this locomotive.

The AUTHOR replied that on the L. & N. E. high pressure locomotive a Gresham and Craven " Combination " injector was fitted which took steam at boiler pressure. It was quite a standard type with loaded overflow and slightly altered nozzle proportions. The Davies and Metcalf injector which was also fitted, worked at 200lbs. sq. in. against 450lbs. sq. in. There was a manifold in the cab which was supplied by steam reduced to 200lbs. sq. in. by means of a reducing valve. The " H " type injector was fed from this manifold together with other auxiliaries.

Mr. Gresley anticipated that by using hot water injectors he would eliminate scaling inside the boiler tubes. The feed water was fed into the front end of the top drum where no tubes existed, and, after depositing its sediment, it flowed over a sill in a comparatively clean condition.

Mr. F. W. J. STROUD said he had noticed that in some of the examples shewn the steam and water were controlled by one handle, and asked if they would work against any pressure as the G.W.R. injector did.

The AUTHOR pointed out that the injectors referred to were designed to adjust the steam and water supplies simultaneously. They were claimed to be so proportioned that when the pressure was varied, the turning of the handle adjusted both the steam and water supplies for the new pressure.

Mr. F. W. WESTLAKE noted that the Author gave particulars of the high velocity which live steam might attain, and asked for a method of calculating this value.

The AUTHOR in his reply said that when steam passed through a nozzle and was expanded, energy, in the form of heat, was liberated. The kinetic energy attained equalled the heat liberated, and then the Author showed how a formula could be obtained to give velocity. It followed, then, that vertical measurement on the Mollier diagram could be used to obtain this value.

Mr. L. J. Hersee mentioned that in the course of the paper the Author had stated that in a hot water injector the water was capable of condensing less steam. It did not appear reasonable that the steam supply should be increased.

The Author answered that apparently this was the case, but the point was that the density became less, so the amount of steam was increased to obtain a bigger velocity, and therefore, having a bigger velocity and less mass, the momentum was altered very little.

A Member stated that in the case of the hot water feed pump there was no loss at the overflow, and asked if it would not be better, therefore, to fit all engines with hot water feed pumps, and only use exhaust steam to heat up the water.

The Author, in describing the systems of feed water heating in use, mentioned that they were very complicated in-so-far as they required two pumps to operate them. It was true they had no overflow, but, although he had no actual figure for waste at overflow, he believed that it did not exceed 7½lbs. per application on a G.W.R. injector. Possibly the cost of such water would not justify having feed heaters worked by pumps, although such systems were in use.

Mr. W. H. Pearce said that, judging from the descriptions given of the different types of steam injectors that had been introduced at various times, there were too many complications to withstand the conditions met with in locomotive practice. Were some of these injectors in use on some sections of the railway the upkeep charges would be excessive.

One of the simplest designs was the G.W.R. restarting injector. This had to work under exceptional conditions, and, even then, in some cases it required attention each week, when the water developed excessive deposit on the cones, etc.

Reference had been made to an experimental G.W.R. injector. This type was much simplified, and it was anticipated that the decreased number of parts and machined surfaces would prove a considerable advantage. It had been proved, on test, to maintain delivery against a good percentage of excess pressure over a large range of steam pressures.

A variable feed injector, under engine working conditions, had yet to be introduced, although recent improvements in exhaust injectors used on G.W.R. engines had made them more satisfactory in this respect. These results were sometimes governed by the method of water inlet, as it was essential to get a good unbroken water jet through the water regulating nozzles without the aid of steam.

The warming of feed water had limitations, as different conditions arose for summer and winter working ; it had been tried on several engines. Also a method of variable feed had been devised by diverting some of the delivery through small apertures to the feed water, consequently increasing the temperature of the latter, thus decreasing the amount injected to the boiler.

Simplicity in design, and parts proportioned so that they would work over long periods with scale forming water, combined with few and easily removable parts, were the main requirements for G.W.R. engines.

The question of waste through the overflow had been discussed. This was frequently due to air leaks through the feed pipe and connections, and not due to the injector nozzles or valves.

It was also found to be advantageous to provide the injector with a method of draining the overflow chamber to prevent a boiling action which sometimes occurred due to a leaking steam valve, when the injector was not working.

Mr. Pearce also stated that the taper of the various cones governed injector performance. For the steam nozzle a similar angle was used both for the converging and diverging portions ; the same angle was also used in the combining nozzle, but a smaller angle was found necessary for the delivery nozzle.

The Author replied that he agreed that the design of nozzles was of vital importance, both in increasing efficiency and in reducing erosion, and certain authorities had claimed that a simple taper was not good enough, and had said definitely that a nozzle should be designed mathematically to follow mathematical curves. This would certainly have helped to produce a stable jet, and, by the reduction of eddies and sudden changes of velocity, it would have reduced the scouring action. Purely theoretical design might not always, however, answer in practice, and a simple conical nozzle was possibly as satisfactory.