INJECTOR TESTS

By

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The injector is an instrument by means of which a jet of steam acting on a jet of water with which it mingles and by which it is condensed can impart to the resulting jet of water a velocity sufficient to overcome a pressure equal to or greater than the initial pressure of the steam. The ability of the injector to force water against a pressure equal to that of the working steam makes it a very valuable instrument for supplying a boiler with feed-water. The essential difference between the injector and the other forms of jet pumps is, that a great part of its energy is derived from the condensation of the steam by the water. The jet pump works on the principle that when a small volume of a fluid moving at a high velocity mingles with a larger volume, it can move the whole volume at a low velocity. This principle enters into the working of the injector for a small amount of steam issuing from a boiler at a high velocity will impart to a large volume of water a considerable velocity, but this is only a small part of the energy developed in the injector. The greater part of the energy, as has already been stated, comes from the heat contained in the steam. On the condensation of the steam this heat is given up and is converted into mechanical energy.

For the invention of the injector we are indebted to Henry Gifford an eminent French engineer. Gifford was interested in the developement of aeronautic apparatus and it became necessary for him to have some light and simple instrument to feed a small boiler which was to be carried by a balloon. The only boiler feeder then obtainable was a heavy and combersome steam pump so he directed his energies toward the invention of some other kind of apparatus. He was acquainted with the methods of pumping water with the steam jet and after a thorough study of the dynamics of steam he concluded that there was sufficient latent energy in steam, not only to move a large volume of water but to force it into the boiler from which the steam came. He wrote and made public a long and complete treatise on the subject, describing in detail the manner in which the principles which he had found might be put into use. He however, did nothing toward the developement of his ideas until several years later.

In 1858, seven years after his first treatise appeared, he took out a patent on an instrument which he called the injector. This injector incorporated in its construction all of the fundamental principles which are utilized in the modern injectors. Gifford's knowledge of the laws which govern the flow of steam was not as extensive as that of engineers of later years and of course slight improvements have been made on his injector embodying the new principles. Gifford's first injector was however, not what would be called a conspicuous commercial success. When it was put to the test of actual service it was found to be imperfect in many respects. But the difficulties were overcome and it required only a few years of developement to make it as reliable and as economical as any instrument in any line of work. The only radical improvement that has been made is the arrangement of the nozzles in such a way as to make it automatic in its action. That is so it will adjust itself to varying steam pressures and varying quantities of feed water. The original Gifford injector had to be constantly regulated by hand to compensate for the varying working conditions.

As is the case with any new invention that makes a striking departure from the ordinary conception of things, the injector was looked upon with a great deal of disfavor when it first make its appearance. It was said by some that the working of the injector was a plain impossibility since it was in direct contradiction to the law of the conservation of energy. The mechanical imperfections of the first injectors gave some ground for contention and Gifford had great difficulty in convincing the engineering public that his invention was a practical one. Continued success however, established the fact beyond a doubt that the injector was a boiler feeder far superior to the steam pump for stationary purposes where the requirements were not exacting. But for use on the locomotive where it was most needed it was not a success until the automatic regulation was developed. The frequent changes of steam pressure and the constant jarring to which it was subjected made constant attention and frequent adjustment necessary causing great inconvenience. Now however, locomotives in the United States are equipped exclusively with the injector though in Europe there still remains some skepticism and the pump is sometimes used. The injector is used extensively for feeding small boilers such as portable and traction engine boilers and small stationary boilers.

Theory of the Injector.

The heat energy in one pound of steam, when saturated and at a pressure of P_1 pounds per square inch absolute, is given by the expression $(x_1 r_1 + q_1)$ where x is the quality of the steam or the actual weight of the vapor, r is the latent heat of vaporization of one pound of steam at the pressure P_1 , q is the heat required to change the temperature of one pound of water from the freezing point to that of saturated steam at the pressure P and is the mechanical equivalent of heat.

The energy in one pound of feed-water entering the injector at a temperature of t_2 may be represented by σq_2 where q_2 is the heat of the liquid at the temperature t_2. The kinetic energy of one pound of water entering the injector with a velocity of V_f is $V_f/2g$ from the fundamental equation for kinetic energy. g, being the acceleration due to gravity. If the delivery water issues from the injector with a velocity of V_D at the smallest section of the delivery tube and has a temperature of t_3, then its heat energy per pound is σq_3 and the kinetic energy is $V_D^2/2g$.

If each pound of steam moves y pounds feed-water there will be y + 1 pounds of water issuing from the delivery tube. From the law of the conservation of energy, the energy in the fluid as it enters the injector must be the same as that when it leaves it, neglecting small losses due to friction and radiation. Hence the sum of the energies of the entering steam and water must equal that of the delivery water or

$\sigma(x_1r_1 + q_1) + y(\sigma q_2 + V_D^2/2g) = (1 + y)(\sigma q_3 + V_D^2/2g)$. Solving for y in this equation an expression may be had by which the number of pounds of water delivered by each pound of steam used may be calculated. Since the quantities V_f and V_D are never large the terms depending on them are small and may be neglected. Also the velocity of flow through a tube is difficult to measure so those terms are not considered. Thus the expression reduces to $y = \dfrac{x_1r_1 + q_1 - q_3}{q_3 - q_2}$ which is the equation commonly used in practice. This equation will be used in the calculation of the experiments which follow. Thus if the steam pressure, the final temperature, the quality of the steam used and the temperature of the feed-water are known the weight of water that should be moved by each pound of steam may be readily calculated.

The Method.

The object of these tests was to get comparisons of the merits of various injectors. Since the function of the injector is to pump water, the greater the amount of water it will lift per hour and the greater the amount of water it will lift per pound of steam used, the better is the injector. Hence the two main objects sought for in these tests were the capacity and the weight of water pumped by each pound of steam used under various working conditions. To get these two quantities the feed-water was weighed before being used and the time required to pump was noted from which the number of pounds handled per hour could be calculated. Then the discharge water was weighed and the difference between this weight and that of the feed-water was the weight of steam used. From this the weight of water moved by each pound of steam could be found.

As a check on the results and as a comparison, the amount of water that should have been pumped in each case was calculated by the formula, $y = \frac{x_1 r_1 + q_1 - q_3}{q_3 - q_2}$ as has been explained. To make these calculations additional observations had to be made to obtain the required data. The temperature of the feed-water was taken and q_1, the heat of the liquid corresponding to that temperature was found in the tables of the properties of saturated steam. The temperature of the delivery water was also taken and q_2 found in the same manner. x_1, the quality of the steam was found by using a throttling calorimeter attached to the main steam pipe r_1 and q_1 the heat of vaporization and the heat of the liquid were also found in the steam tables.

In order to get reliable results it was necessary to get the weights of the water very accurately for any error in either weight would introduce a relatively large error into their difference or the weight of steam used and make the results valueless. Two platform scales were used, one to weigh the feed-water and the other the delivery-water and a barrel was placed permanently on each one. The feed-water barrel was filled and weighed and the delivery-water barrel was weighed empty. The balancing weight on the beam of the feed-water scale was then moved back until it read ten or fifteen pounds light and the injector was started. The water that was pumped while the injector was being adjusted was delivered into a waste-water barrel. As water was being taken from the feed-water barrel its weight was approaching that for which the scale beam was set and just as the beam fell, the delivery-water was turned into the delivery water barrel by means of a three-way valve. To stop the test the poise weight on the beam of the feed-water scale was set to read several pounds light as before and just as the beam fell, the delivery water was redirected into the waste-water barrel. Accurate weights could thus be obtained by one observer and all confusion avoided.

The time was noted at the beginning and end of each test and readings of the steam pressure, back-pressure, feed and delivery water temperatures and the pressure and temperature in the calorimeter were taken at regular intervals. The average of these readings were taken as the true readings and were used in the calculations.

Each injector was tested at several different steam pressures varying from fifty to one hundred and ten pounds gage, the temperature of the feed-water being kept constant. Since the commercial rating of injectors is usually made at eighty pounds gage pressure, two tests were always made at that pressure to make the results more conclusive. Then tests were made with various temperatures of feed-water the steam pressure being kept constant at eighty pounds gage. Besides these tests another was made to find the minimum steam pressure at which the injector would work satisfactorily, another to find the maximum back-pressure it would overcome with a steam pressure of eighty pounds gage and still another to find the minimum feed-water temperature at which it would work.

When one condition of the test was changed all of the others were kept as nearly constant as it was possible to keep them and similar tests were made with each injector under as nearly the same conditions as could be had so that comparisons of the merits of the various injectors could be made directly from the tabulated results.

The Apparatus

The steam used in these tests was taken from the boiler of a twenty horsepower Avery Traction Engine. This consisted of a four inch pipe about twelve inches long, closed at either end with a cap. Into the cap on the upper end was screwed a quarter inch pipe to which was attached a rubber tube leading to a manometer tube, and two half inch pipes one of which was the steam pipe and the other a receptacle for a thermometer. This latter tube protruded inward about eight inches and outward one inch, the unner end being plugged to prevent the escape of steam. The tube contained several ounces of mercury which made a complete metallic connection between the thermometer and the steam inside the calorimeter. To the lower end of the calorimeter was attached an inch pipe, the exhaust which led the steam away from the calorimeter to the atmosphere. Both the steam pipe and the exhaust were provided with gate valves so that the flow of steam through them could be regulated. The body of the calorimeter was heavily lagged with hair felt to prevent radiation and conduction of heat. The felt was in turn enclosed in a light brass cylinder as a protection to the lagging.

To operate the calorimeter the exhaust valve was opened and live steam was admitted through the steam valve until the pressure as indicated by the manometer, was slightly above that of the atmosphere. Steam was allowed to pass through in this way for several minutes and then the pressure and temperature in the calorimeter and also the pressure in the main steam pipe were taken. From the data thus obtained the quality of the steam could be calculated for the steam was throttled or wiredrawn as it came through the inlet valve and was superheated as it entered the calorimeter on account of the great decrease of pressure. Since there was no loss of heat from radiation or conduction there must have been the same number of B. T. U. in each pound of steam in the calorimeter as there was in the steam pipe. The heat in one pound of steam in the steam pipe could be found in the steam tables and is indicated thus $xr + q$. Since the steam in the calorimeter is superheated its heat is indicated by the expression $\lambda_1 + c_p(t_s - t_1)$ where λ_1 is the total heat of dry saturated steam at the pressure in the calorimeter and c is the specific heat at constant pressure of superheated steam. The value commonly taken for c_p is .48. Equating these two expressions and solving for x, gives the equation $x = \frac{\lambda_1 + c_p(t_s - t_1) - q}{r}$ in which all of the quantities in the right hand member are known.

The pipes leading from the steam main to the calorimeter and injector were lagged with hair felt to prevent loss of heat.

In order to have the conditions the same as those in actual service it was necessary to have some kind of an apparatus in connection with the delivery pipe that would give a back pressure equal to that of the steam in the boiler so that the injector would deliver against the same pressure that it would in practice. The device used depended for its action upon the resistance offered to a stream of water when it passes through an orifice. It consisted essentially of a cylinder one and five-eights inches in diameter in which fitted a long annular piston. The length of the piston was three inches and the cavity measured two and one-half inches from the lower or open end. Extending from one-half inch from the boiler was of the return-flue type, similar to the Scotch marine boiler, with a large steam dome on top from which steam could be taken nearly dry. The boiler was located in a small frame building upon one wall of which was fixed the rest of the apparatus used. This consisted essentially of a steam separator, a throttling calorimeter, an injector, a back-pressure valve and a water-jacketed delivery pipe.

The steam was taken from the top of the steam dome by a two inch pipe which run horizontally overhead to the wall, then vertically downward to within three feet of the floor, then horizontally and parallel to the wall for three feet and then vertically upward thus forming a "U" shaped tube which was fastened rigidly to the wall bu iron supports. A valve was placed in the pipe just above the boiler and another at the other end of the system. The latter was kept closed constantly. In that part of the pipe that formed the bottom of the "U", was placed a steam separator, the separator forming a part of the tube. Thus all of the steam that left the boiler had to pass through the separator and most of its moisture was taken from it. A small water-glass on the side of the separator, near the bottom, indicated the amount of water that had collected. This amount was kept constant by draining off small quantities at intervals through a cock at the bottom.

After passing through the separator the steam rose in the vertical pipe to a point where two pipes were attached, one a half inch pipe leading to the calorimeter and the other an inch pipe leading to the injector. The calorimeter was of the well known throttling type invented by Professor Peabody. It upper end of the piston to near the bottom, were openings, one-eight inch wide, through its annular walls so that water entering the cavity from the bottom would pass out, the top of the piston being closed. When not in operation the piston rested in the upper end of the cylinder so that the openings were completely closed by the walls of the cylinder, but when the water began to press upon the bottom of the piston it would rise and uncover the tops of the openings and allow the water to escape. To the top of the piston was attached a rod which carried a flat iron disc on its upper end. To produce a back pressure, weights were placed on the disc which would move the piston downwards decreasing the area of the openings through which the water could pass and this increased the resistance which the water would have to overcome to get through. To vary the back pressure the number of weights on the disc were changed until the desired pressure was secured.

To provide for the proper pipe connections to the back pressure valve, a two and one-half inch "T" was screwed on each end of the cylinder, the middle opening of each extending outward. One opening of the lower "T" was plugged while the delivery tube from the injector entered at the other. The middle opening of the upper "T" led to a one and one-fourth inch pipe through which the issuing water was conducted to the weighing barrel. Into the upper opening of the upper "T" was screwed another cylinder similar to the first which served as a stuffing box for the piston rod. The back pressure was indicated by a steam gage which was attached to the valve where the water entered. Connection between the injector and the back-pressure valve was made by means of a steam hose. This tube was used in order to have considerable flexibility to provide for the connection of various makes of injectors. To provide for taking the temperature of the delivery water, a thermometer cup, similar to that in the calorimeter, was placed in the delivery pipe near the injector.

The pipe which led from the back pressure valve to the delivery barrel was about fourteen feet long and was surrounded by a three inch pipe which served as a water jacket. Cold water was kept constantly circulating in this jacket to cool the delivery water. The water as it issued from the injector had a temperature of about one hundred and seventy degrees Fahrenheit and if it was not colled considerable, evaporation would occur and cause an error in the results. The cooling water was collected in an elevated barrel to be used in the tests with high temperature feed-water.

Tests were made with steam pressures varying from fifty to one hundred and ten pounds gage, at intervals of tem pounds. Pressures higner than one hundred and fifteen pounds could not be carried on the boiler used, and since an injector is seldom required to work at a pressure lower than fifty pounds, no extensive tests were made below that pressure. It was inconvenient to get a pressure below fifty pounds in the boiler so to make the low pressure tests, the steam was throttled down to the desired pressure by closing the valve on the main supply pipe near the boiler. This throttling would of course, tend to dry the steam and give steam of a different quality than that used in the other tests, but the separator took out all but about three percent of the moisture in any case, so that if any difference resulted it was slight.

The distance which the injector lifted the water was three and one-half feet in all cases.

The accompanying photograph shows the arrangement of the apparatus used.

The Injectors

Tests were made on four injectors, a Hancock inspirator, a Metropolitan automatic injector, and two Penberthy injectors.

The Hancock inspirator is a double-jet injector with two sets of tubes, similar to those in the simple injector, set side by side. Steam and water mingling in one combining tube, the resulting mass being forced into the other combining tube where it meets another and larger jet of steam by which it is forced out through the delivery tube to the boiler. The operation is thus divided into two stages, the first in which a relatively large volume of water is given an impulse by a small jet of steam and the second in which the whole volume is given a second impulse by a new and larger jet of steam. This division of the work between the two sets of tubes makes the duty of each much lighter and makes their action flexible so that it will adjust itself readily to changed conditions. The second combining tube has a diameter of only about half that of the first and since the second steam jet is the larger of the two, the greater part of the velocity of the water is attained in the second tube. The feed water is heated to a high temperature and given a small velocity in the first tube which relieves the second tube of a great part of the whole duty.

This inspirator has a valve on the overflow which is closed when the instrument is started so that there is no water emitted at the overflow no matter what interruption might occur. When the action of the inspirator is interrupted, steam is immediately blown out into the feed water tank causing a loud cracking sound which indicates that it will not start again without the usual starting operations.

The inspirator used in these tests bore the type number of ten and had half inch pipe connections.

The only distinguishing feature of the Metropolitan injector is the movable steam nozzle, the position of which is controlled by a threaded spindle. By rotating this spindle the steam nozzle is moved inward or outward and the distance between it and the combining tube regulated to suit the conditions. The spindle also regulates the cross-sectional area of the steam nozzle through which steam is allowed to pass.

The instrument used in these tests was of the type A and size three and one-half. All connections were for one-half inch pipe.

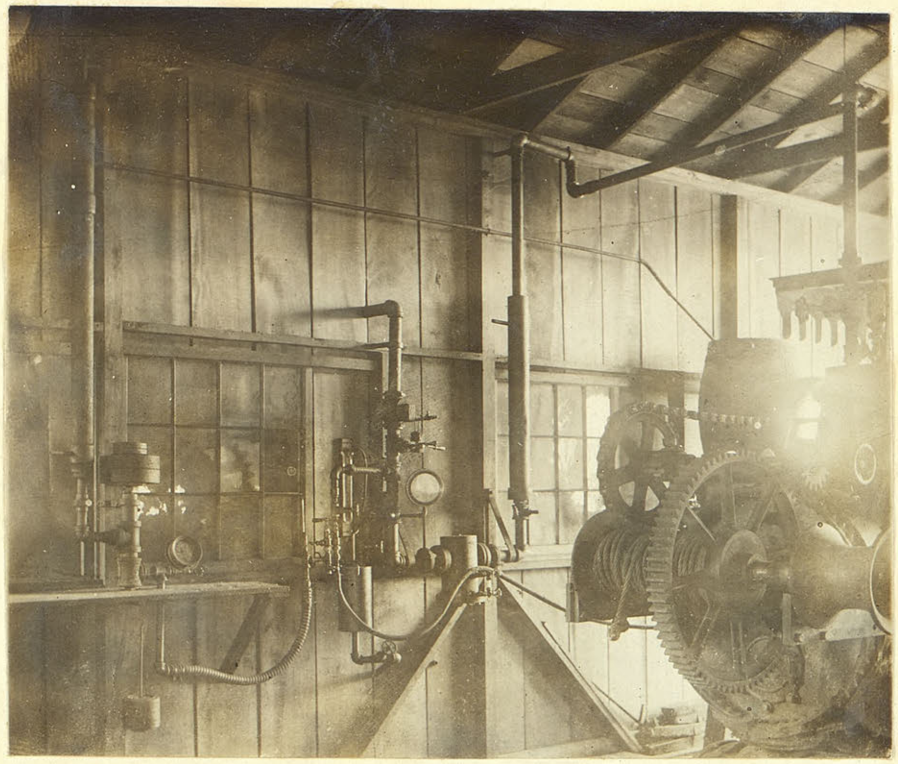
The Penberthy injector is an injector very much like the Metropolitan in the arrangement of the tubes and nozzles but has not the movable steam nozzle and hence can be controlled by regulating the supply of steam and water by valves outside the injector.

The two Penberthy injectors used in these tests were of the type A and size twenty-one, all connections being for half inch pipe. One had been in service for several years while the other had never been connected to a boiler.

The injectors tested were numbered consecutively, one, two, three, and four, the numbers having no reference to the order in which they were tested nor the order in which the names have appeared here-to-fore. Their numbers appear on the data sheets, the names being omitted entirely.

Of the four injectors tested only three were put through the complete test as outlined, these were numbers one, two and three. Number four was used in making preliminary test to find the best methods of operating and to get the whole system into good working order. In these preliminary tests an effort was made to keep the steam and back pressure constant throughout each test so the calculations could be made in round numbers, but it was found to be very difficult to keep those quantities constant so in the other tests readings were taken at intervals and the averages taken as the proper readings. The data taken in the preliminary tests though probably not quite so accurate as the others, was never the less reliable and was tabulated with the other data. No account was taken in this set of tests of the time so that the weight of water pumped per hour could not be calculated.

Two tests were made on the Metropolitan injector, the only difference being that the first was made without any reference to the temperature of the delivery water, so that no comparisons could be made between the experimental and the theoretical results since the temperature of the delivery water is required in the theoretical calculations.



SUMMARY OF INJECTOR TESTS

Injector No.	1	2	3	
Capacity Lbs. per hour	970.7	1066	1040	
Water delivered per lb. of Steam	11.2	11.05	12.4	
Maximum permissible back pressure	121	105	102	105
Minimum " " "	16	18	24	35
Minimum " feed water Temperature	97	97	98	95

K E Y   S H E E T

#1 Inspirator

#2 Metropolitan

#3 New Penberthy #

#4 Old Penberthy #