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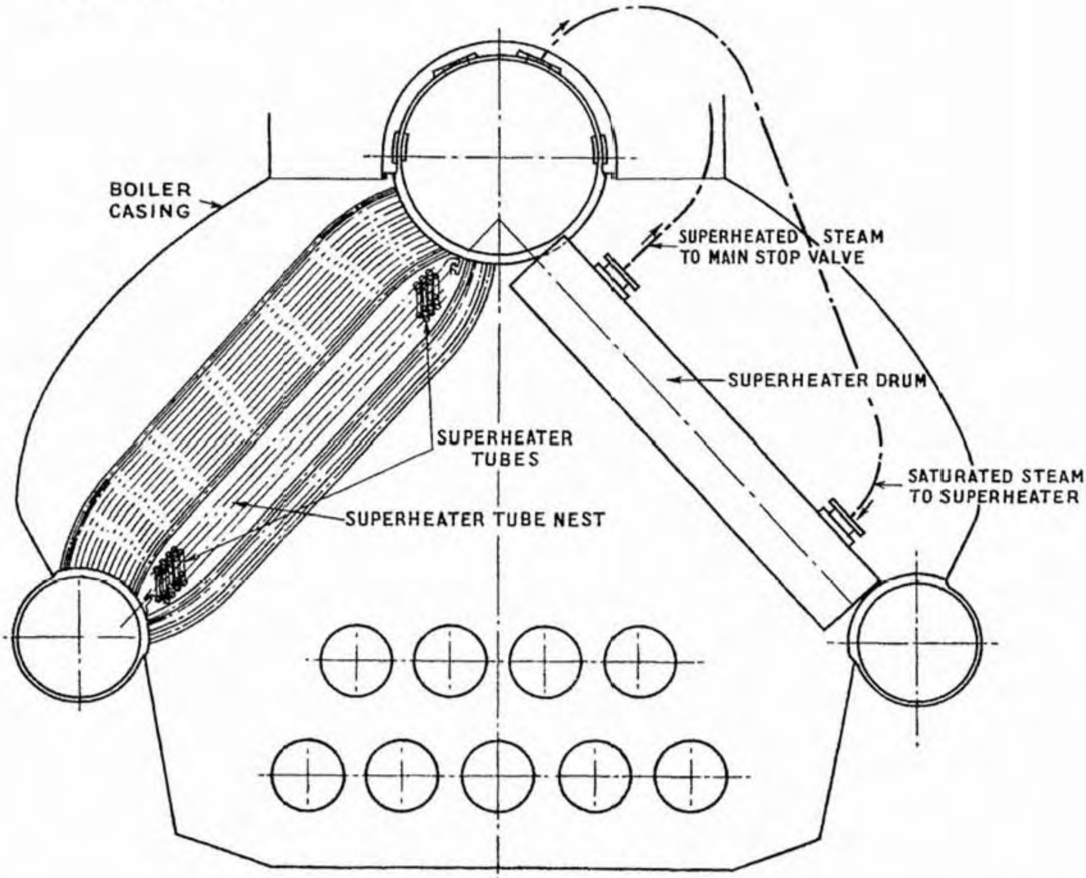
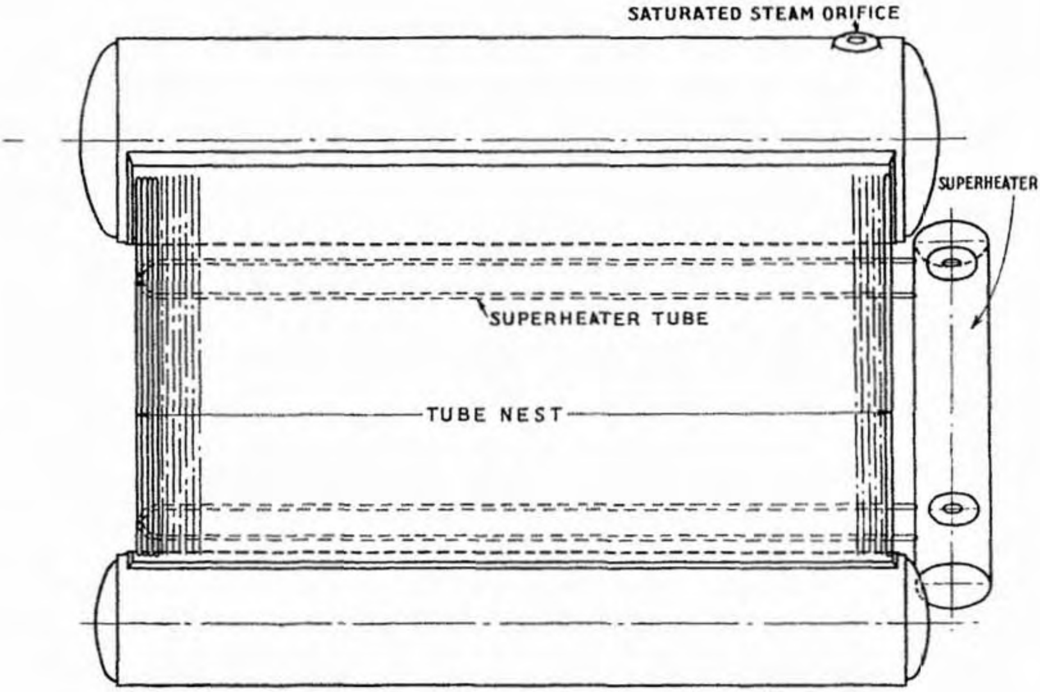


FIG.
Admiralty Super



1.

heat Boiler.

No. 2

NAVAL WATER-TUBE BOILERS

[*Read before the Institution of Naval Architects, 2nd April,* 1936, *and reproduced by permission of the Institution.*]

Experiments and Tests.—In Papers on Engineering Subjects No. 14, particulars were given of developments in naval water-tube boilers and experiments and trials leading up to those developments.

In the present Paper an account is given of some further tests and experiments which have since been carried out at the Admiralty Fuel Experimental Station, Haslar, on three-drum type boilers with the object of obtaining more intimate information regarding the internal working conditions which might enable further improvements in the efficiency and reliability of water-tube boilers to be effected.

By internal working conditions is meant the supply of feed-water and its circulation, the changes in the state of the water in circulation, the generation of steam and its removal from the boiler.

A typical arrangement of an Admiralty three-drum type superheated boiler is shown in Fig. 1.

In this boiler the first two rows of tubes next to the furnace on each side are of $1\frac{3}{4}$ in. external diameter, while the remainder are of $1\frac{1}{8}$ in. external diameter.

The superheater is fitted in the space between the fourth and fifth rows of tubes in each bank.

The feed-water is usually supplied by a turbine-driven feed-pump which discharges the feed-water through a float-controlled feed regulator and thence through the internal feed-pipe situated in the lower part of the steam drum.

A slotted internal steam pipe is fitted, through which the steam passes to the superheater and thence through the stop-valve to the main steam pipes.

Boilers of this type can be forced to fairly high rates, and the trend of development is towards obtaining the greatest output consistent with efficiency and reliability in order to keep the weight of the boilers and the space occupied to a minimum. This development results in the boilers becoming reduced in size and weight in proportion to the output obtained, and one important effect of the reduction in size is the reduction in steam reservoir capacity of the boilers. When the speed of the engines is changed rapidly, this reduction in reservoir capacity makes it necessary that the output of the boiler must be capable of being increased or decreased rapidly, in order to meet the varying requirements for steam.

It is a well-known fact that alteration of the output of a water-tube boiler causes a change in the apparent water-level as indicated by the water gauges. When the output is increased the water-level rises temporarily in the gauge glass and when it is decreased the water-level falls temporarily. If changes in output are made rapidly they may, in extreme cases, lead either to water passing over with the steam, with consequent loss of superheat or possible damage to machinery, or temporary loss of water resulting in overheating of the boiler tubes.

Investigations have been carried out with an old pattern Yarrow boiler of the size and type fitted in the " W " class destroyers. The general arrangement of the boiler is shown in Fig. 2. This boiler has four rows of $1\frac{1}{2}$-in. tubes and thirteen rows of $1\frac{1}{8}$-in. tubes in each bank.

In addition to the usual water-level gauges fitted to the boiler, an additional gauge was installed consisting of a number of water gauges connected to a long stand-pipe, the upper end of which was connected to the steam space and the lower end to the bottom of the water pocket. This gauge is subsequently referred to as the " Overall " gauge.

When the output of the boiler was increased the water-level in the overall gauge fell very rapidly below the level indicated in the ordinary water gauge as shown in Fig. 3. This was mentioned in

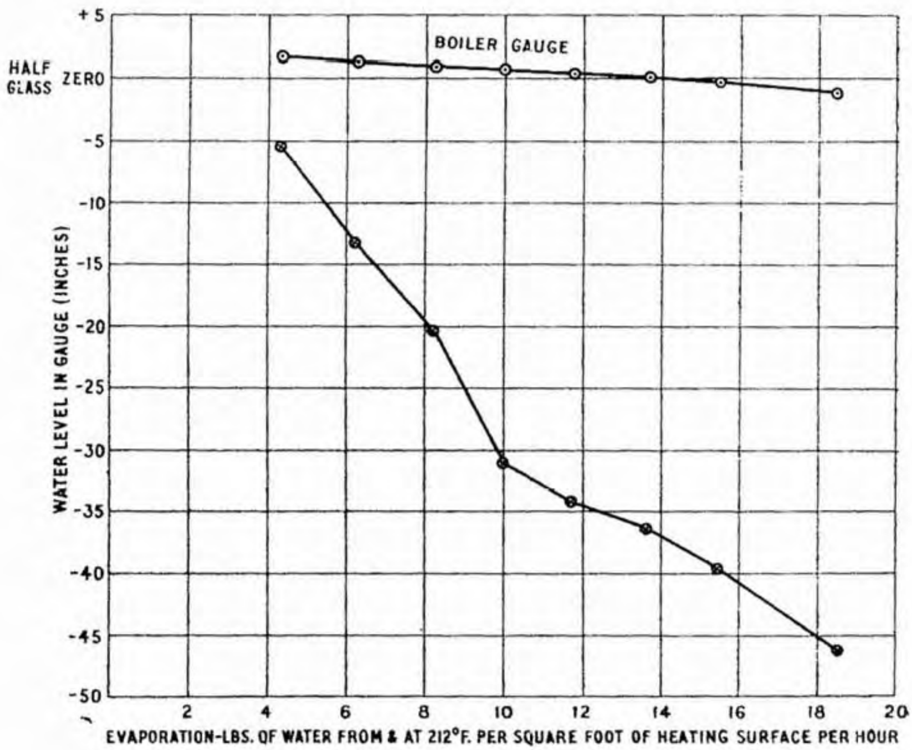


FIG. 3.
Overall Gauge Readings.

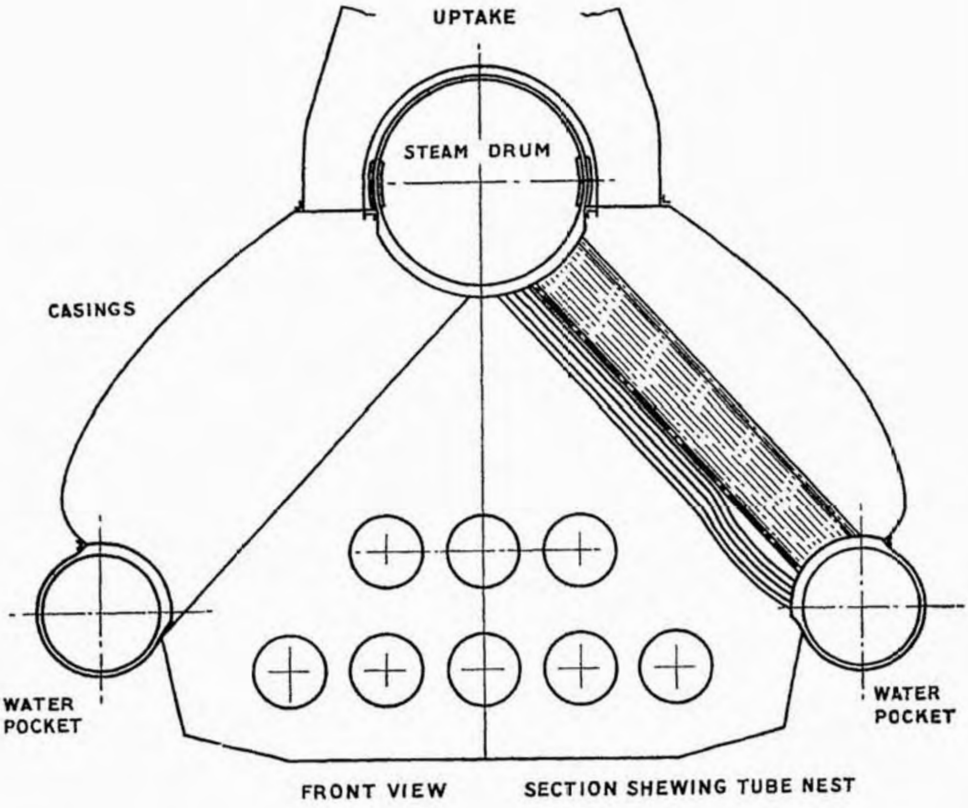

UPTAKE
STEAM DRUM
CASINGS
WATER POCKET
WATER POCKET
FRONT VIEW
SECTION SHEWING TUBE NEST

FIG.

Test

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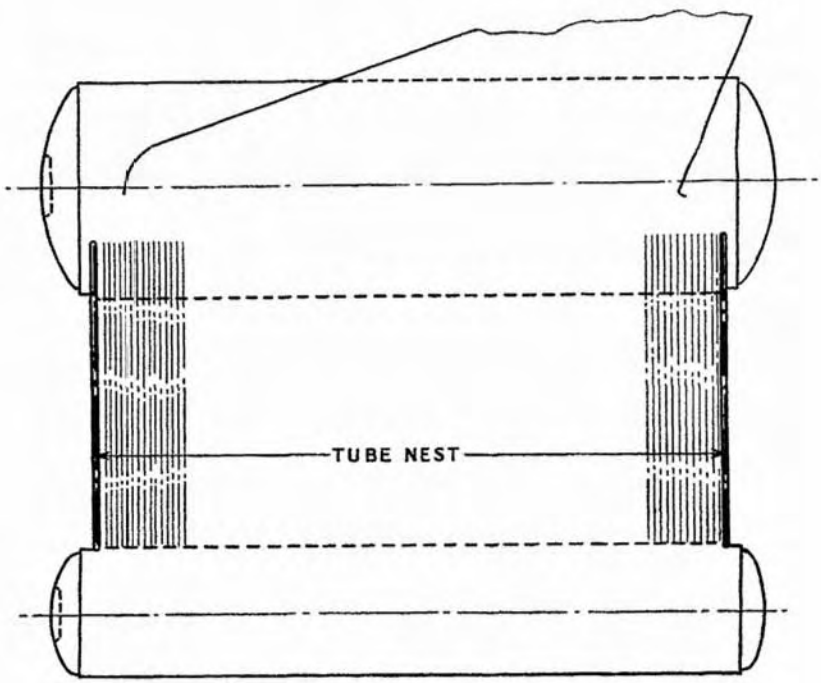


2.
Boiler.

the earlier Paper referred to, and appears to be due to the fact that when steam is being generated there is in the boiler a mixture of steam bubbles and water in circulation, and as the rate of steam generation is increased the proportion of steam bubbles in the mixture is increased and causes a reduction of density of the mixture in circulation, until at full power its density is approximately two-thirds of the density of the water at the same temperature.

A curve showing the density at different rates of output as deduced from these readings is shown in Fig. 4. The rapid change

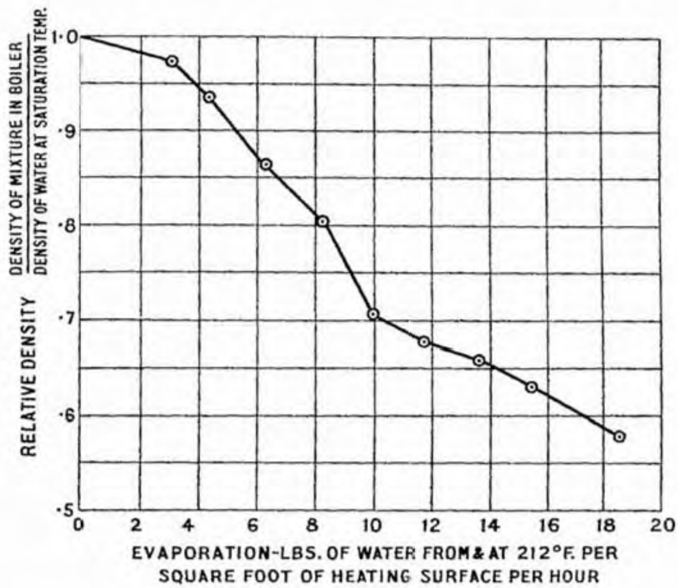


FIG. 4.

Relative Density and Output.

in density which will be noted at about one-quarter to one-half of the full output of the boiler, appears to indicate that the rate of steam generation at that output is sufficient to cause a general turbulence in the mixture in the steam drum with the result that there is a large increase in the amount of steam carried in the water in circulation. Before and after this change has taken place, the ratio of density to output appears to vary in a more regular manner.

A simpler and less cumbersome indicating apparatus has been devised. This consists of a U gauge containing mercury, one end of which is connected to the water connection of one of the water-level gauges and the other end to the lower part of one of the water pockets. The difference in the height of the mercury in the two parts of the U tube indicates the difference between the weight of the column of water in the connecting pipes and the weight of the column of mixture in the boiler, from which the density of the mixture of steam and water in the outer rows of boiler tubes can be deduced.

Circulation in Boilers.—The results of the investigations into the changes in density naturally led to consideration being given to the effect of these changes on the circulation in the boiler, and investigations into the circulation of the water in the boiler tubes were made by means of Pitot tubes. The apparatus is shown in Fig. 5, and a description of it, which was given in the earlier Paper is again given in the Appendix.

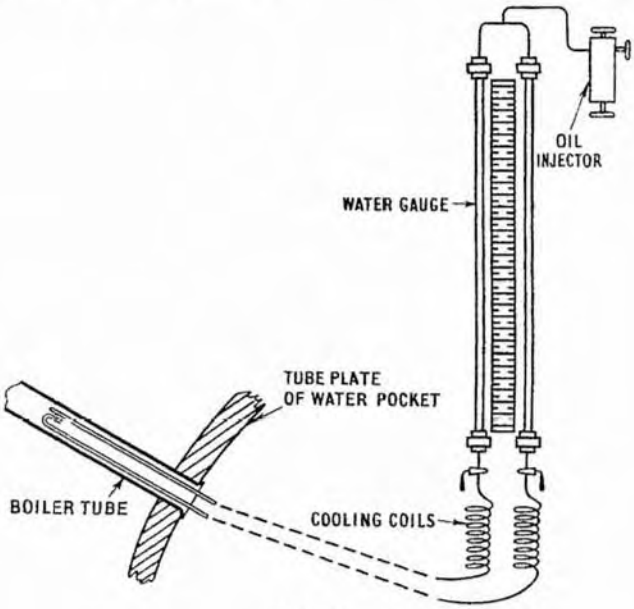


FIG. 5.

Pitot-tube Apparatus.

The Pitot tube was inserted, in each case, in the lower end of the boiler tubes and connected to the indicator which gave an indication of the velocity head. In order to translate the readings of velocity head into velocity or mass flow in the tubes, it is necessary to know the density of the mixture of steam and water passing the Pitot tube, and the density in the outer tubes as shown by the readings of the overall gauge has been taken as indicating approximately the density of the mixture passing.

These investigations indicated that there was, in general, an upward flow in the first four or five rows of tubes from the furnace and a much smaller flow in a downward direction in the remainder of the tubes. At low outputs there was an upward flow in a larger proportion of the tubes in the tube nests nearer the back wall, *i.e.*, the end of the boiler remote from the oil burners, than in the tube nests nearer the front of the boiler, while at high outputs the conditions tended to level up along the boiler. This appears to be due to the fact that the hot gases pass towards the back of the boiler at low outputs, giving a higher temperature at the back than at the front of the furnace.

The mass flow in several representative generating tubes is shown in Fig. 6, and it is noted that while the downward flow in

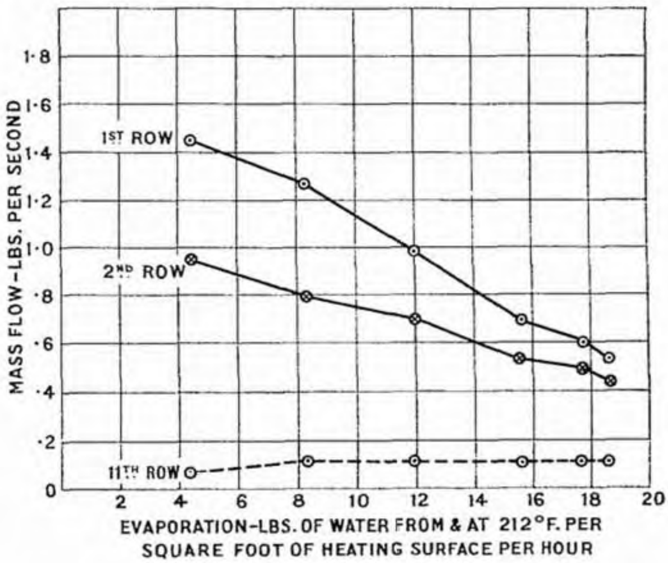


Fig. 6.

Mass Flow in Generating Tubes.

the outer rows remains low at all outputs, the upward flow in the fire-row tubes decreases at high outputs. This is contrary to the usual supposition that the circulation becomes more rapid as the rate of steam generation increases.

Circulation is caused by the mixture in the rows of tubes near the furnace being less dense than the mixture in the outer rows, as by far the larger proportion of steam is generated in the fire rows. In other words, the head of the mixture in the outer rows becomes greater than the head in the fire row. The generation of steam in the rows of tubes near the furnace produces an increase in volume of the mixture of steam and water as it passes up the tubes, and the velocity of the mixture leaving the tubes will therefore be greater than the velocity when entering the tubes. The increase in momentum of the mixture as it passes up the tubes is provided by a portion of the head causing circulation. At high outputs it appears that the head required to produce the increase in momentum increases at a greater rate than the head causing circulation, with a resulting reduction in the rate of circulation.

Theoretical calculations indicate that the mass flow in the fire-row tubes will depend directly on the density of the mixture and also indicate that the generation of steam in the tubes will tend to reduce the mass flow at high outputs. These calculations are given in the Appendix. This slowing down of the circulation sets a limit to the rate of steam generation beyond which overheating of the fire rows will occur.

It was found that irregular conditions of boiler feeding affected the indications given by the Pitot-tube apparatus, and a sudden change in the feed supply often produced a reduction in the flow in the fire-row tubes when steaming at high powers. On a number of occasions a reversal of the circulation in a fire-row tube has been experienced and appeared to be due to a sudden change in the feed supply. It was also found that, with the usual feed arrangements, the results obtained were frequently inconsistent.

Feed Supply.—It was formerly the practice to introduce the feed-water into the lower water pockets, but this was changed and the feed led into the steam drums on account of the corrosion which was found to take place in the water pockets and the lower ends of the boiler tubes. The corrosion was caused by the gases which were liberated from the feed-water as it became heated by contact with the boiler water. With modern closed feed systems and de-aerated feed-water, this corrosion would be less likely to occur.

An examination of the feed-supply arrangements showed that with the internal feed-pipe in its usual position, *i.e.*, at approximately the centre of the lower part of the steam drum, the relatively cold feed supply was discharged immediately above the fire-row tubes which normally acted as risers, and it appeared that the feed-water tended to flow down the tubes and interfere with the circulation. For the single internal feed-pipe, shown in Fig. 7, two pipes were substituted and arranged towards the sides of the lower part of the steam drum and arranged to discharge the water outwards in order to keep it away from the fire-row tubes (Fig. 8).

With the new feed-pipes, more consistent indications have been obtained with the Pitot-tube apparatus.

The change in the position of the feed delivery pipes was found to affect the density of the mixture in the boiler, and comparative trials, the results of which are shown plotted in Fig. 9, show a definite increase in the density due to this change.

The increase in density gives improved conditions for the fire-row tubes as it produces an increase in the mass flow through those tubes.

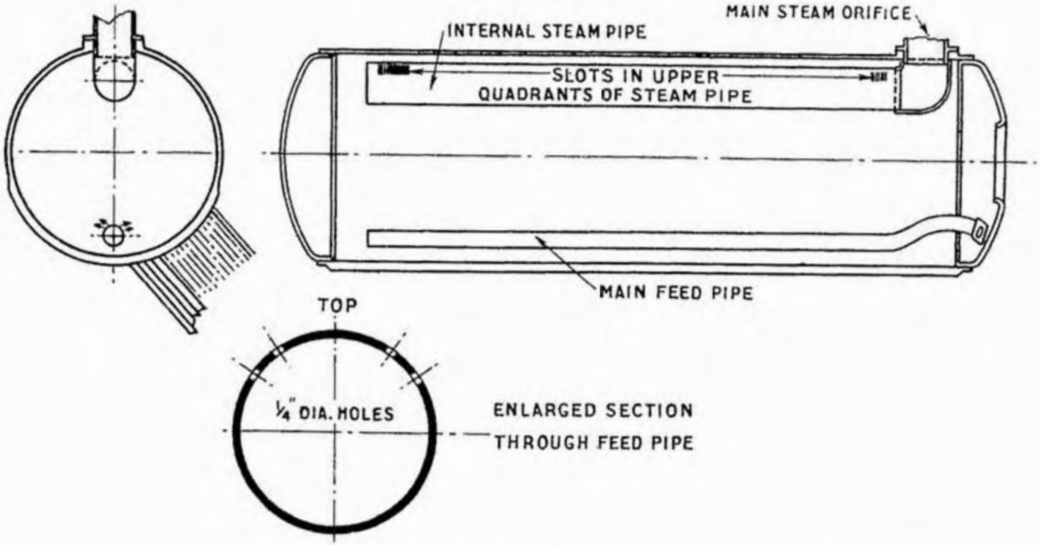


Fig. 7.

Steam Drum of Boiler Showing Internal Steam Pipe and Original Feed Pipe.

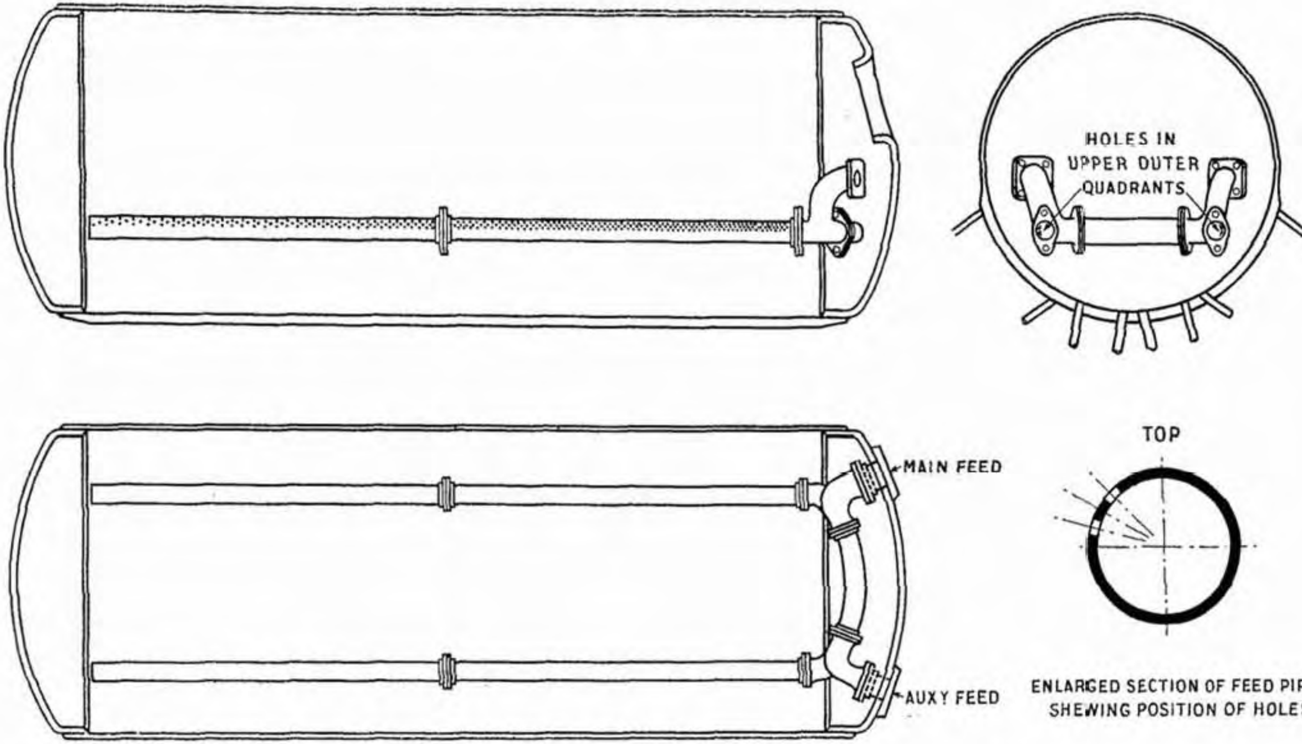


FIG. 8.

New Design Feed Pipes.

These results indicate that the new arrangement of feed-pipes should add to the reliability of the boiler, by reducing the tendency towards overheating of the fire-row tubes at high powers.

Overheating of Fire-row Tubes.—For the purpose of easier reference Fig. 10 has been reproduced from the earlier Paper already referred to. This diagram shows an estimate of the percentage heat transfer to the separate rows of tubes in a three-drum type superheater boiler and indicates the large proportion of the heat which is absorbed by the fire-row tubes.

This high rate of heat transmission makes the fire-row tubes more liable to overheating than the remainder of the tubes, and an improvement in the conditions under which these tubes operate must first be obtained before any great increase in the rate of forcing of such a boiler can be made.

This can be effected in several ways :—

(*a*) By increasing the diameter of the fire-row tubes without changing their length.

The volume of water contained in each tube is proportional to the square of the tube diameter while the heating surface of the tube is proportional to its diameter. An increase in the diameter will, therefore, result in an increase in the amount of water, or mixture of steam and water, in the tube per unit of heating surface. Advantage is already taken of this, and the tubes nearer the furnace are made $1\frac{3}{4}$-in. in diameter as compared with $1\frac{1}{8}$-in. diameter for the remainder of the tubes.

Any considerable increase in the size of these tubes would result in an increase in tube thickness and higher heat stresses on that account. It has also the disadvantage of increasing the weight of the boiler and producing an undesirable increase in the stiffness of the fire-row tubes. On account of the greater space which the larger tubes occupy in the tube plate, there will be a reduction in the number of rows of tubes it is practicable to fit without increasing the size of the steam and water drums.

(*b*) By arranging water walls in the furnace to receive a proportion of the radiant heat and so relieve the fire-row tubes to some extent. This is already done by many boiler designers in a number of ways, and is widely adopted for land installations, but, in general, appears to be difficult to apply to this type of boiler without undue increase in weight and complication.

(*c*) By increasing the circulation in the rows of tubes which are nearer the furnace.

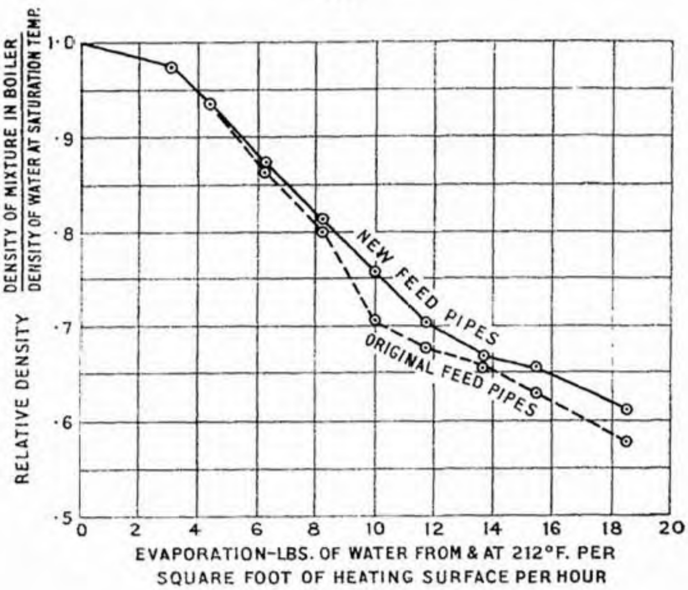


Fig. 9.

Relative Density and Output.

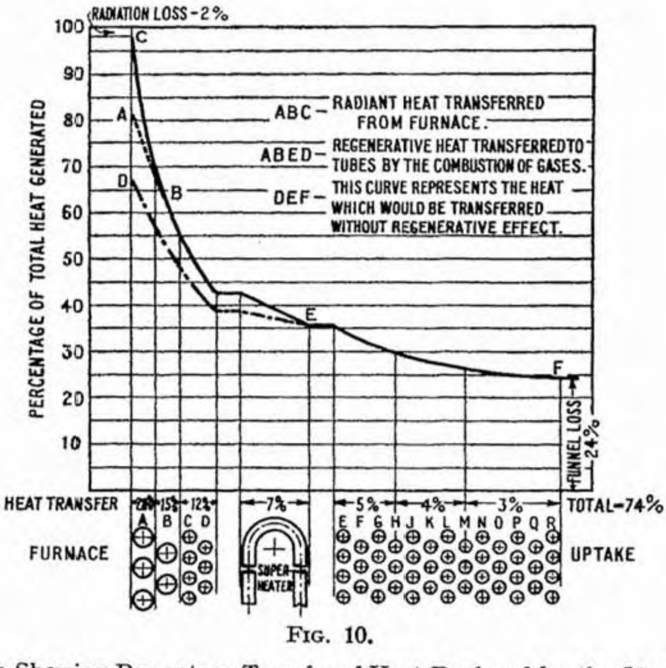


Fig. 10.

Diagram Showing Percentage Transfer of Heat Produced by the Combustion of Fuel at 0·85 lbs./ft.² Heating Surface Per Hour.

The circulation in a water-tube boiler can often be improved by fitting large external downcomer pipes properly arranged between the steam drum and water pockets.

The effect of fitting external downcomer pipes is to increase the area for downward flow, and, as the mixture of steam and water passing down the downcomer pipes will have no heat put into it, the mixture will contain a smaller proportion of steam than that which passes down the outer rows of generator tubes. The mixture entering the water pockets and passing into the fire-row tubes would therefore be increased in density by the addition of downcomers. To produce a definite improvement, the area of the downcomers should be large in view of the large area of generator tubes which already act as downcomers and, to ensure that they are supplied with a mixture of steam and water of the greatest density, the downcomers should be connected to the lowest part of the steam drum.

The increase in weight and space caused by the fitting of the downcomer pipes is a definite disadvantage, and the rigidiy of these large pipes between the steam and water drums may give rise to troubles due to the expansion of parts of the boiler being more restricted.

It has already been mentioned that, by a rearrangement of the feed-pipes, some improvement in the circulation in the fire rows has been effected.

In view of the large proportion of heat absorbed by the tubes nearer the furnace, it would appear that the greater proportion of the steam generation takes place in those tubes, and the mixture of steam and water discharged into the steam drum from their upper ends will contain a much larger proportion of steam and, therefore, have a much lower density than the mixture in the steam drum.

With the object of allowing the steam to escape from the fire-row tubes more freely by relieving the tubes of the back pressure due to the head of the mixture in the steam drum, an experiment was carried out with one of the fire-row tubes extended into the steam drum to the full output water-level as indicated in Fig. 11. The boiler was worked up to full output with the Pitot-tube apparatus in use. This was repeated with the extension pipe removed, and the results showed that there was an improvement of flow in the tube when the extension pipe was fitted, the improvement being greatest at high outputs. At full output the increase in flow was approximately 25 per cent.

The delivery of the steam and water from the generating tubes into the steam drum above the level of the water in it was provided for in the Belleville boiler where similar internal pipes were fitted in the steam drum, and, in the early Thornycroft boilers, all the generating tubes were expanded into the upper part of the steam drum so that they delivered the steam and water above the water-level in the drum. In these boilers the whole of the downward flow passed through the external downcomers.

This is arranged also in the Babcock & Wilcox boiler and in many others.

It would, however, be quite impracticable to fit such extensions, in a three-drum type boiler, to all the tubes having upward circulation, and the following arrangements were made in order to meet this difficulty. A large trough was built in the steam drum with its lower edges attached to the tube plate and extending approxi-

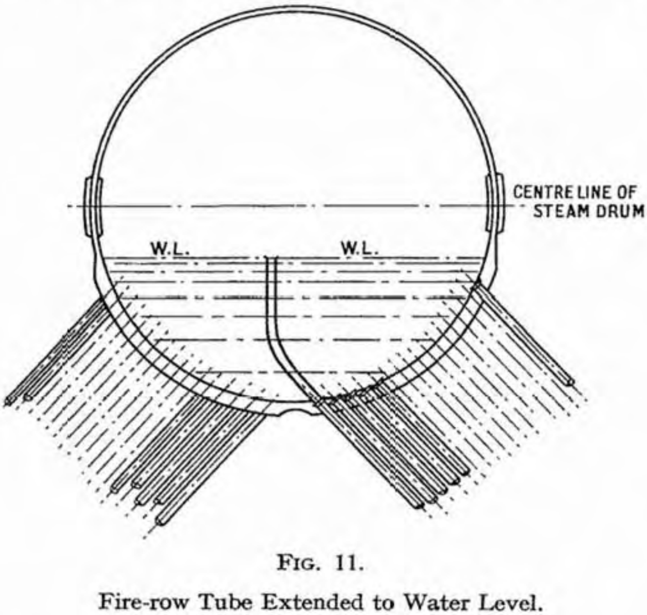
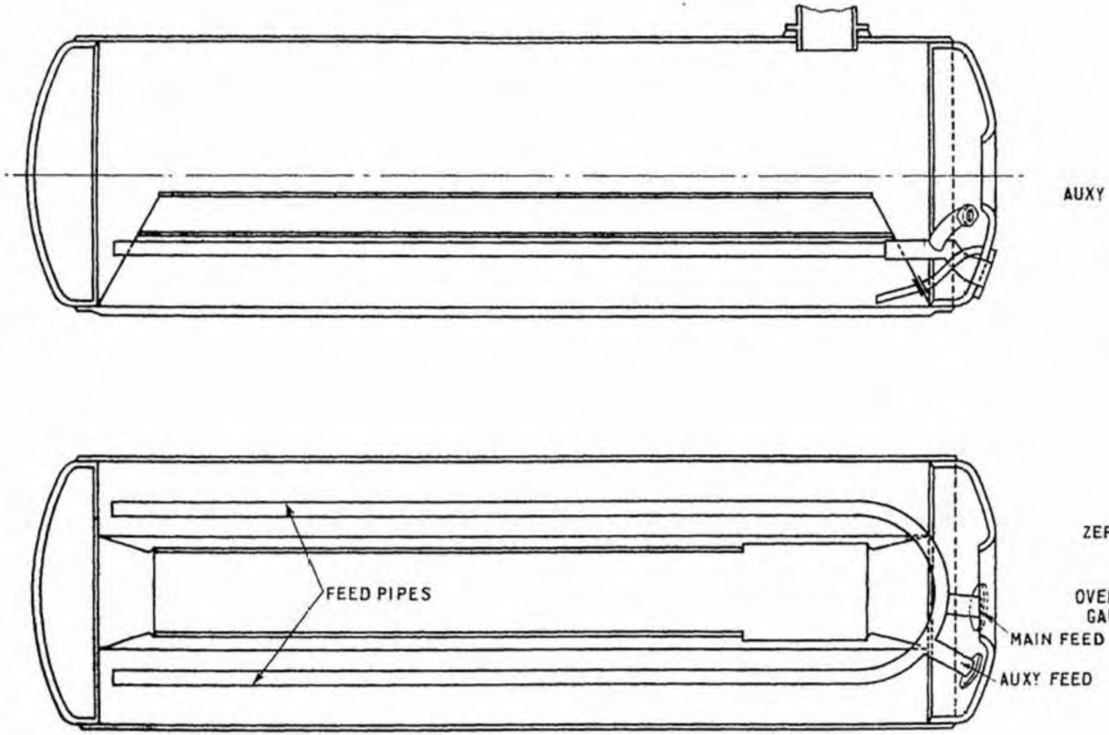


FIG. 11.

Fire-row Tube Extended to Water Level.

mately to the normal full output water-level, and so arranged that the rows of tubes near the furnace discharged into it. The trough was open at the top and this formed one large extension tube which led the discharge from the tubes, enclosed within its borders, up to the water-level and took the place of the large number of separate extension tubes. The ends of the trough were closed and were so shaped to give ample communication space between the portions of the steam drum on each side of it.

The feed-pipes were arranged in the method already described, along the sides of the lower part of the steam drum, to deliver the feed-water into the space outside the trough. In this way the feed supply assists the circulation in the boiler and does not interfere



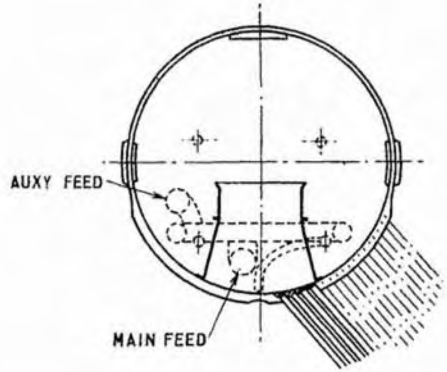
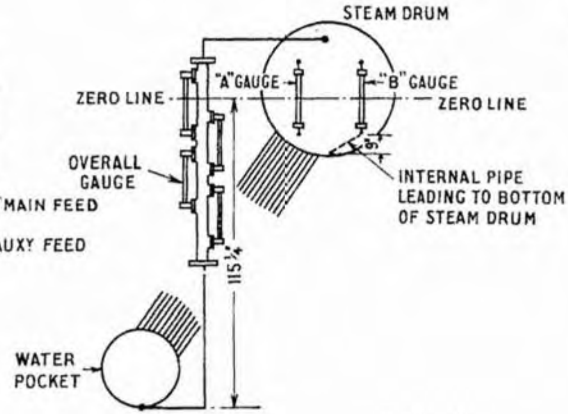


FIG. 12.

Circulation Augmentor as Fitted for Trials.



arrangement of water gauges.

with the free exit of the steam and water from the generator tubes which discharge into the trough.

This apparatus will be referred to as a Circulation Augmentor.

The arrangement of the circulation augmentor, as fitted for tests, is shown in Fig. 12.

Trials were carried out with the circulation augmentor fitted to the boiler shown in Fig. 2, and the trough was arranged to contain the ends of the first four rows of tubes on each side of the furnace.

The Pitot-tube apparatus indicated that there was a considerable improvement in circulation at high outputs as compared with the circulation at the same outputs when the augmentor was not fitted, and no reversals of flow in the fire-row tubes were experienced.

The curves in Fig. 13 indicate the mass flow in tubes in the first five rows from the furnace, and show that at high outputs the

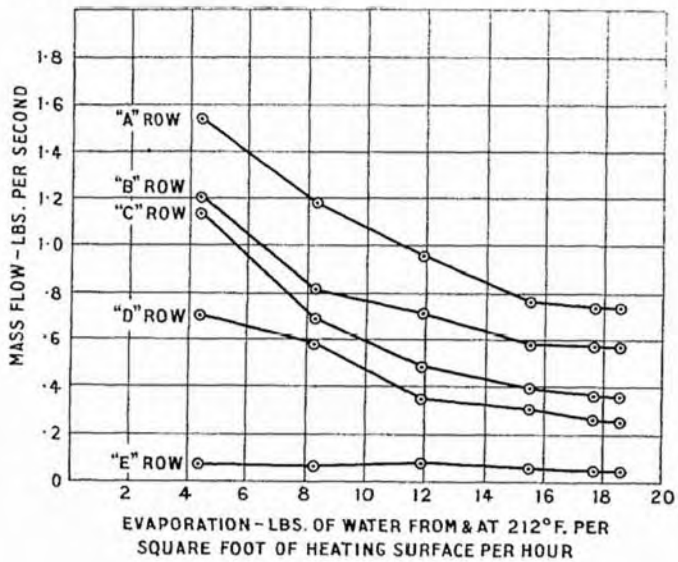


Fig. 13.

Mass Flow—Fire-row Tubes.

circulation falls off much more slowly as the output is increased than was the case when the augmentor was not fitted.

It was found that in the portions of the tube nests near the back wall of the boiler there was an upward circulation in all the tubes, including those outside the augmentor at low outputs, but, as the output of the boiler was increased, the outer rows of tubes began to act as downcomers and at one-third output and above there was an upward circulation in the first five rows only. In the tube nests at the centre and towards the front of the boiler there was an upward circulation in the first five rows at all powers, the tubes in all the outer rows acting as downcomers.

In view of the nature of the apparatus used and the conditions under which the readings were taken, the figures quoted for mass flow are only approximate, but give a definite indication of the changes in the rate of circulation under the different conditions.

From the estimated mass flow in the tubes at different parts of the boiler, an approximate estimate indicates that the total upward flow was about ninety times the amount of water evaporated when the boiler was working at one-quarter output. At half output the upward flow was reduced to twenty times the amount evaporated and at full output it was further reduced to only eight times the amount evaporated.

The readings of the overall gauge indicate that the density of the mixture of steam and water in the boiler at all outputs was higher due to the fitting of the augmentor. From this it appears that the steam generated in the fire-row tubes is enabled to pass more freely into the steam space and is entrained with the water in circulation to a less extent than before.

To obtain some information as to the density of the mixture of steam and water in the trough above the fire-row tubes, an internal pipe was fitted to the lower connection of one of the water-gauge glasses and led to a position 1 in. above the lowest part of the steam drum. When the augmentor was fitted, the pipe was led through a watertight joint in the end of the trough to the same position above the lower part of the steam drum inside the trough. This pipe is shown in Fig. 12. This gauge is referred to as gauge " B."

The water in gauge " B " above the end of the internal pipe is balanced by the head of mixture of steam and water above the internal pipe in the steam drum and so indicates, in terms of head of water, the head of the mixture of steam and water above the upper ends of the fire-row tubes.

When the augmentor was fitted, the level in gauge " B " was much lower than when the augmentor was not fitted, although the water-level in the boiler gauge was kept the same in both cases. This indicates that the density of the mixture inside the trough and above the fire-row tubes is much less than the density of the mixture in the same position in the steam drum when the augmentor is not fitted. This reduction in pressure at the outlet of the fire-row tubes and increase in density of the mixture at the inlet to the tubes would account for the increase in the rate of circulation shown by the Pitot-tube readings.

The results obtained with these gauges are shown in Fig. 14.

A comparison of the curves of density deduced from the data obtained with the overall gauge in Fig. 15 with those in Fig. 9, indicates that the decrease in density of the mixture in the boiler with increase of rate of evaporation is much more regular when the augmentor is fitted than without it, and this confirmed the observations of the behaviour of the boiler, the working of which was much steadier with the augmentor fitted.

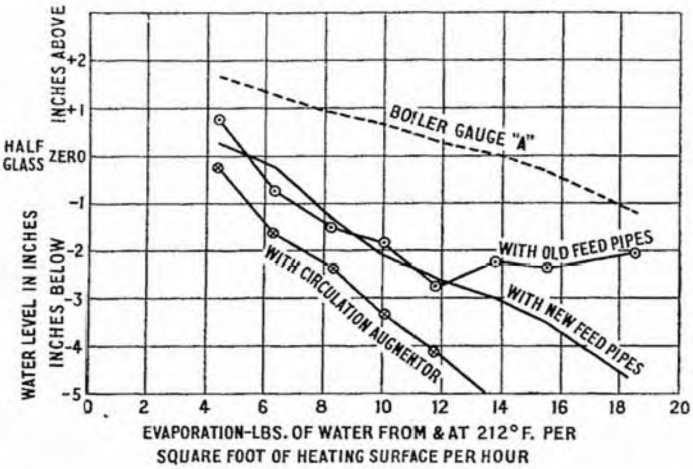


FIG. 14.

Readings of " B " Gauge.

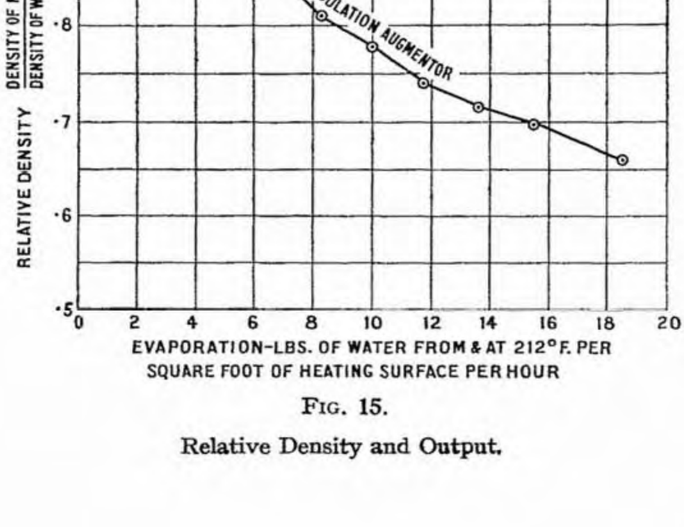


FIG. 15.

Relative Density and Output.

The arrangement of the generator tubes in the Admiralty superheater boiler lends itself very readily to the fitting of the circulation augmentor, as the first four or five rows of tubes in which normally there is an upward flow are separated from the remainder by the superheater tubes. The presence of the superheater, moreover, reduces the temperature of the gases entering the tubes on the uptake side of the superheater, with the result that the heat put into those tubes is relatively small compared with that put into the fire-row tubes. In this type of boiler the rows of tubes before the superheater are led into the augmentor, and there is a convenient space on the tube plate for its attachment.

To test the effect of the augmentor on the circulation in one of these boilers, the boiler was first tested without the augmentor and worked at a high rate of evaporation. The tubes were then carefully examined and the boiler again worked at a slightly higher rate, and this procedure was continued until it was found that two of the fire-row tubes had become overheated. The rate of evaporation at which this occurred was 20·3 lb. of water per hour from and at 212° F. per sq. ft. of heating surface at a rate of oil burning of 1·4 lb. per hour per sq. ft. of heating surface. No signs of overheating were observed when the boiler had been worked at a rate of evaporation of 19·6 lb. of water per hour from and at 212° F. per sq. ft. of heating surface at a rate of oil burning of 1·3 lb. per hour per sq. ft. of heating surface. The normal maximum rate of evaporation of the boiler was 15·7 lb. of water per hour from and at 212° F. per sq. ft. of heating surface at a rate of oil burning of 1 lb. of oil per hour per sq. ft. of heating surface.

The overheated tubes were replaced by new tubes and the circulation augmentor was fitted to the boiler. The boiler was then worked at increasing rates up to the maximum rate of forcing practicable with the existing fuel and air system, without any signs of overheating. The maximum rate of evaporation attained was 22·3 lb. of water per hour from and at 212° F. per sq. ft. heating surface at a rate of oil burning of 1·61 lb. of oil per hour per sq. ft. of heating surface.

During trials at sea, another boiler fitted with the augmentor has been worked at a rate of evaporation of 21·75 lb. of water per hour from and at 212° F. per sq. ft. heating surface without any signs of overheating.

Steam Pressure and Circulation.—The tests described have been carried out with boilers working at 250-lb. pressure and 300-lb. pressure.

It has been suggested that a water-tube boiler working at high steam pressures would probably have a poorer circulation than a boiler working at low steam pressures on account of the greater density of the steam at the higher pressure.

In order to compare the circulation in a boiler at different steam pressures, the circulation as indicated by the Pitot-tube apparatus was measured in a boiler working at full output at a steam pressure of 250 lb. per sq. in., and the density of the mixture of steam and water in the boiler measured by means of the overall gauge. The steam pressure was then reduced to 170 lb. per sq. in. and the boiler worked for some time at the same rate of evaporation. The circulation was found to be reduced and the density of the mixture of steam and water in the boiler was also found to be reduced. This test has been repeated on several occasions with the same result. The actual decrease in rate of circulation in a fire-row tube was approximately 18 per cent. and the decrease in density approximately 9 per cent.

These results indicate that the circulation in a water-tube boiler increases as the working pressure increases, and a water-tube boiler working at a high steam pressure would be less liable to failure due to poor circulation at high outputs than a boiler working at low steam pressures.

Internal Steam Pipes.—The internal steam pipes fitted in the steam drums of water-tube boilers usually extend over the greater part of the length of the steam drum and are provided with transverse slots of uniform pitch and size, cut in the upper surface of the pipe, as shown in Fig. 7. Their purpose is to collect the steam along the length of the upper portion of the steam drum and prevent, as far as practicable, drops of water thrown up in the drum as the result of ebullition, from entering the steam pipe. The clear area through the slots is usually made about twice the area of the pipe or 2½ times the area through the stop valve seat. The pressure drop through such a pipe is about 5 or 6 lb. per sq. in. at full output, and as this pressure drop could readily be reduced by increasing the size of the slots, experiments were carried out in order to ascertain the effect of such a change on the action of the internal steam pipe as a collector of steam along the steam drum.

To obtain some indication of the distribution of the flow of steam through the separate slots along the length of the internal steam pipe when fitted in a boiler, the internal steam pipe was removed from a boiler and secured to a boiler-room bulkhead with the pipe parallel to the bulkhead. The pipe was fitted in such a way that the air from the boiler-room passed through the slots in the pipe, then along the pipe and through the elbow-piece at the end of the pipe and out of the boiler-room through a hole in the boiler-room bulkhead. The air passed through the pipe in the same way as steam would pass through it when fitted in the boiler.

An anemometer, fitted to a box which was shaped to cover a group of slots, was used to measure the air supply to those slots, and by moving the box to cover different groups of slots the distribution of the air supply to the slots along the length of the pipe could be measured.

The internal steam pipe tested was taken from the boiler shown in Fig. 2, and was of 10 in. internal diameter and provided with slots $\frac{1}{8}$ in. wide and 4 in. long arranged on each side of the crown of the pipe. The total area through the slots was 175 sq. in. and the pipe area 80 sq. in. The stop valve area was 71 sq. in. The ratio of area through the slots to the area of the internal steam pipe was 2·2 to 1 and the ratio to the stop valve area 2·46 to 1.

An air pressure of 3 in. of water was maintained in the boiler-room.

The mean velocity of air through the slots was 14·6 ft. per sec. The steam velocity through the slots was 44·5 ft. per sec. at full output when the internal steam pipe was in the boiler. The velocity of air through the slots near the outlet end of the pipe was 69 ft. per sec. as compared with a velocity of only 7·6 ft. per sec. at the far end of the pipe. This indicates that, when in the boiler, the collection of steam along the drum was far from uniform, the larger proportion entering the internal steam pipe near the outlet end.

A second test was made with the alternate slots blanked, reducing the area through the slots to 1·1 to 1. Under these conditions the velocity varied from 69·7 ft. per sec. at the outlet end to 28·1 ft. per sec. at the far end of the pipe, and showed that a more even distribution was obtained by reducing the area through the slots. It followed, therefore, that to increase the area through the slots, in an endeavour to reduce the pressure drop, would result in a more uneven distribution along the pipe.

Tests with another pipe were carried out with different ratios of area through slots to area of pipe, varying from 4 to 1 to 2 to 1, with an air pressure of 2 in. of water.

Tests with the air pressure increased to 6 in. of water showed that the velocity of air through the slots was increased proportionately along the pipe, and that the distribution does not change with velocity. From this it appears that the results obtained indicated what would happen when the internal steam pipe was in a boiler.

Curves showing the results obtained are shown in Fig. 16.

From an examination of these results, it appeared that the distribution along the pipe could be made more uniform by reducing the size of the slots near the outlet end and increasing the size of the slots towards the far end of the pipe.

For simplicity in manufacture, a pipe was marked off in 10 equal portions and the pitch and size of the slots made uniform in each portion. With a clear area through the slots equal to three times the area of the pipe, the area of the slots in each of the portions, starting from the outlet end, varied from 9·5 to 89·2 per cent. respectively of the area of the pipe. This arrangement of slots gave an approximately uniform distribution of air along the pipe, and when fitted in a boiler would ensure a sensibly uniform collection of steam along the length of the steam drum.

The pressure drop through an internal steam pipe designed on those lines and fitted to a boiler was found to be approximately one-half that of the normal pipe, and the dryness of the steam delivered was found to be the same as that produced when the normal internal steam pipe was fitted.

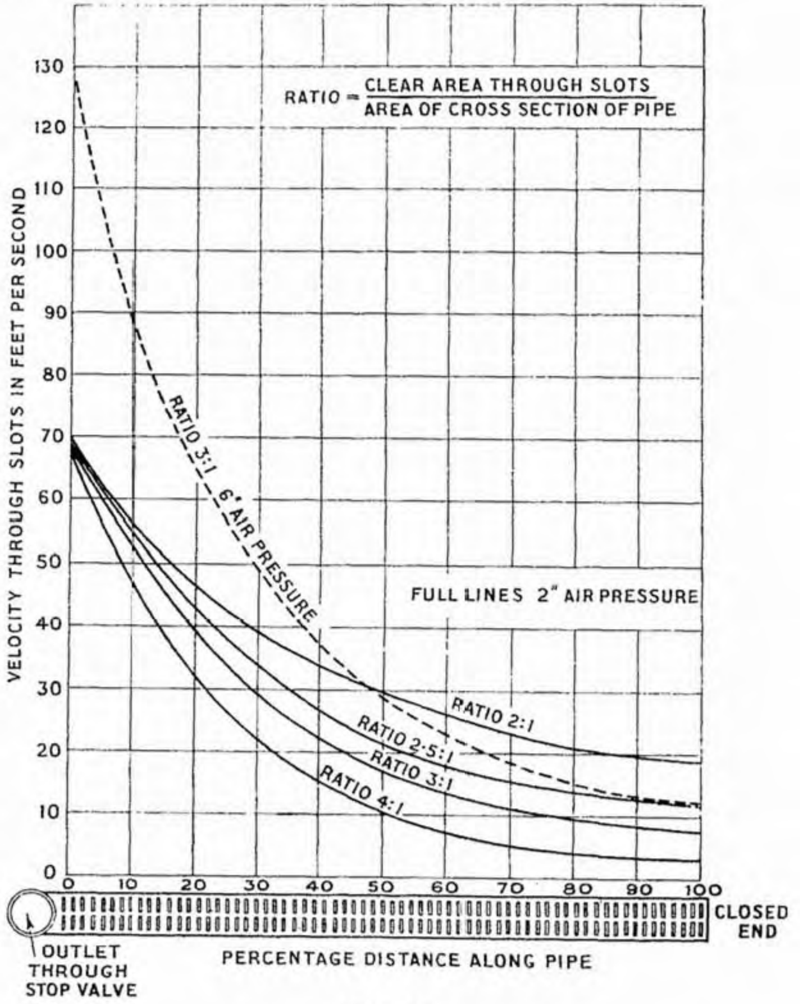


Fig. 16.
Velocity Through Slots of Internal Steam Pipe.

During the tests with the different internal steam pipes, the effect of raising the water-level in the boiler on the dryness of the steam was noted. The raising of the water-level caused the steam to become wet, with the result that the degree of superheat was reduced.

The relation between the height of the water in the gauge glass and the degree of superheat was noted while the boiler was worked at a steady output.

In one of the internal steam pipes tested, the slots were made longer than in the other pipes, with the result that the lower edges of the slots were $\frac{1}{2}$ in. nearer the water-level in the steam drum. With this internal steam pipe in use it was found that for the same degree of superheat it was necessary to keep the water-level in the boiler exactly $\frac{1}{2}$ in. lower. This appeared to indicate that the height of the slots or steam outlet orifices above the water-level was a controlling factor in the dryness of the steam.

The internal steam pipe was then removed altogether, thus raising the outlet orifice approximately 3 in.

It was found that the same degree of superheat was produced when the water-level was raised approximately 3 in. above the water-level required when the internal steam pipe was fitted, other conditions being identical on both tests.

This experiment was repeated in the boiler of a seagoing ship with similar results.

The results obtained on these tests are shown in Figs. 17 and 17A.

These tests appear to indicate that in boilers of this type working under service conditions with distilled feed-water, it is possible to dispense with the internal steam pipe without any loss of superheat, provided the steam outlet is at the highest part of the steam drum.

When the circulation augmentor is fitted, the steam is discharged from the fire-row tubes at a high velocity when the boiler is worked at high rates of evaporation, and it has been found necessary to fit the internal steam pipe or other form of baffle to prevent particles of water being projected into the outlet orifice.

Internal Feed-Pipes.—The feed-water is usually discharged into the boiler through internal feed-pipes which extend along the greater part of the length of the steam drum, and consist of steel pipes closed at the far ends and perforated with holes equally pitched along the sides or upper surface of the pipes. The discharge of water from the holes in such a pipe is not uniform along its length, as the motion of the water along the pipe tends to make the larger proportion of the water flow out through the holes at the far end of the pipe and a relatively small proportion flows out through the inlet end.

The problem is somewhat similar to that already described in the case of the internal steam pipe, and in the case of the internal feed-pipe it is necessary to provide a large number of holes near the inlet end and a smaller number at the far end, if it is desired to produce a uniform distribution of the feed-water along the steam drum.

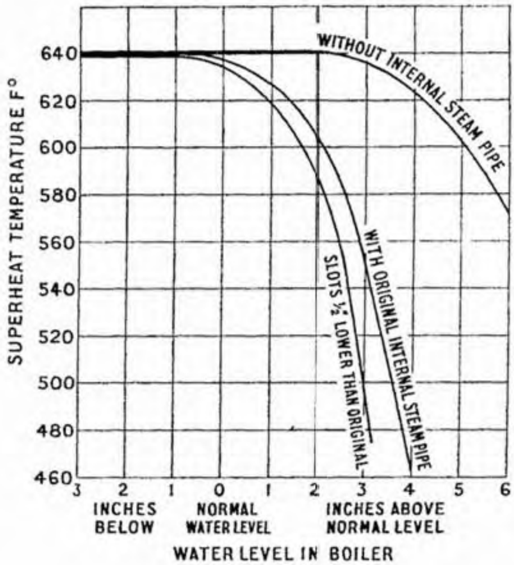


FIG. 17.

Effect of Water-level on Superheat.

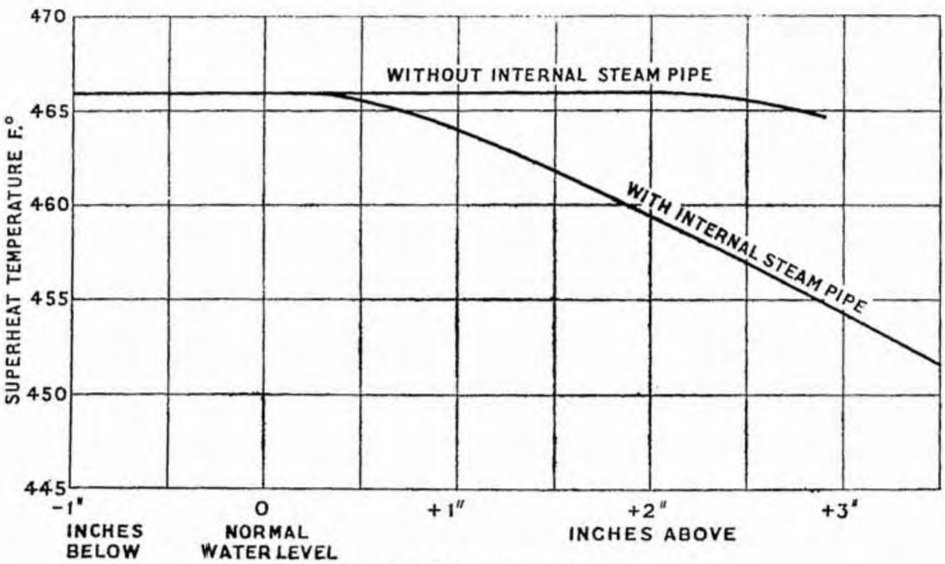


FIG. 17A.

Effect of Water-level on Superheat Trials at Sea.

It was found by experiment that in a feed-pipe in which the total area of the holes was equal to 2·5 times the area of the pipe, if the pitch of uniform size holes is arranged to vary from 0·43 to 1·56 times the mean pitch from the supply end to the closed end, the discharge is sensibly uniform along the length of the pipe, and so produces a uniform distribution along the steam drum.

Operation of Boilers.—It has already been pointed out that rapid changes in the output of, or in the rate of supply of feed-water to a water-tube boiler at high rates of evaporation, result in rapid changes in the state of the mixture of steam and water in circulation in the boiler, and the modifications in the feed-pipes, already referred to, have been made in order to give a more uniform distribution of the feed-water in the boiler and assist in keeping the circulation steady and regular.

In order to maintain steady conditions in the boiler, at the different rates of evaporation, it is essential that the feed supply should be kept as constant and regular as practicable for each rate of evaporation. It is found to be a difficult operation to regulate, by hand, the feed supply to a modern highly forced water-tube boiler in order to produce the steady conditions desired, and when the demand for steam from the boiler is subject to changes, as it is when frequent changes of speed are required, this operation becomes increasingly difficult. The effect of a considerable increase in the feed supply is temporarily to retard the generation of steam and to increase the density of the mixture of steam and water in circulation in the boiler. As a result, the water-level in the gauge glass does not rise as it would naturally be expected due to the increase in feed supply, but falls, and more feed-water is supplied in order to maintain the water-level. This causes a temporary reduction in steam pressure. Exactly the reverse happens when the feed supply is reduced considerably, the water-level rises temporarily instead of falling, with a result that a further reduction in feed is made to meet that condition, with consequent rise in steam pressure.

These large changes in the feed supply produce very unsteady boiler conditions which result in undesirable changes in steam pressure and unsteady working of the machinery.

These changes in conditions can be avoided if the changes in feed supply are made gradually.

Automatic Feed Regulators.—It is, therefore, very important that the automatic feed regulator should be thoroughly reliable and should give a steady control of the feed supply without over-feeding or underfeeding, as any tendency of the feed regulator to feed intermittently or to "hunt" becomes exaggerated by the action of the boiler.

It is the usual practice in naval vessels to heat the feed-water in pressure feed heaters on the discharge side of the feed pumps, where the heating agent is the exhaust steam from the auxiliary machinery.

The auxiliary exhaust steam is condensed in the feed heaters, and if the feed supply is unsteady the rate of condensation of the auxiliary exhaust steam will be unsteady and the pressure in the auxiliary exhaust will fluctuate. This fluctuation in the auxiliary exhaust pressure causes unsteady working of the auxiliary machinery, particularly when working with the closed feed system, and produces unsteadiness in the supply of air to the boilers and interferes with the action of the feed system, and, in many cases, makes the boiler plant very difficult to control. The need for a high standard of steadiness of control by the feed regulator is, therefore, of primary importance.

In order to test the behaviour of feed regulators under working conditions, the following system was adopted. The feed regulator was fitted to a destroyer type boiler on shore and the feed-water supplied at constant pressure by a turbine-driven feed pump. The feed-water was supplied from two measuring tanks and the amount used was measured every 30 seconds. The water-level in the boiler was noted at the same time. The boiler was worked at low power with one burner in use at 100-lb. oil pressure until steady conditions were obtained, when measurements were taken over an interval of 7½ minutes' duration.

A second burner was then put into use and a similar set of measurements taken. A third burner was then put into use and the procedure continued until eight burners were in use, and finally the oil pressure was increased to 135-lb. pressure to produce full power conditions at a rate of oil burning of 1·28 lb. per sq. ft. of heating surface.

After the last 7½-minute period had expired the output was reduced. First the oil pressure was reduced to 100 lb. and the burners were shut off two at a time at 2-minute intervals until only two burners were in use, then one burner was shut off to bring the conditions back to those at the start. By this system the rate of feeding could be observed at all rates of output, and the behaviour of the feed regulator could be noted when the output of the boiler was rapidly changed as it would be in a ship when the speed of the engines was rapidly changed.

The results of a satisfactory test of a feed regulator are shown in Figs. 18 and 19.

These curves show the sudden rise in water-level which takes place each time the output of the boiler is increased, and the sudden decrease in water-level when the output is decreased. It will be noted that the rate of feeding is steady when one burner is in use, and when the second burner is put into use the water-level rises, due to the decrease in density of the mixture of steam and water in the boiler, and the feed regulator reduces the feed supply until the water-level in the boiler falls, then gradually increases the feed supply until steady conditions are again reached. This action is repeated as each additional burner is put on and again as the oil pressure is increased.

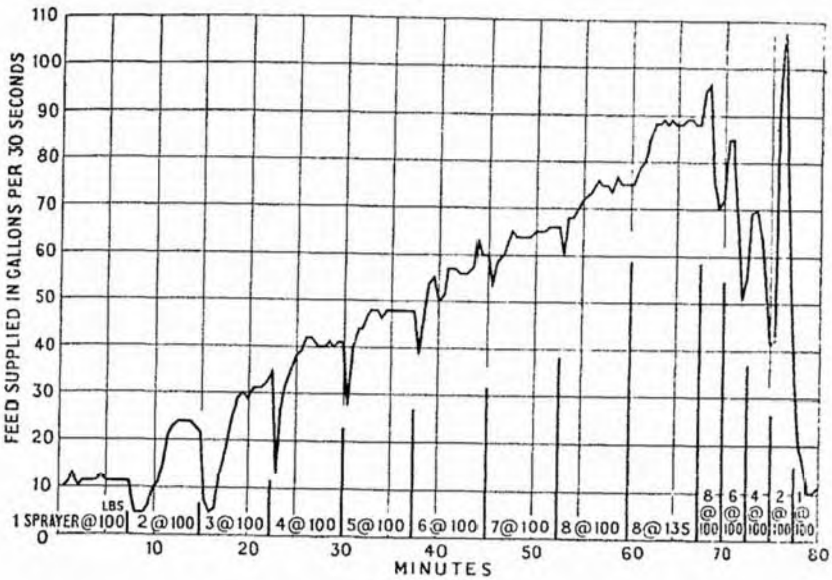


FIG. 18.

Test of Feed Regulator—Feed-supply Measurements.

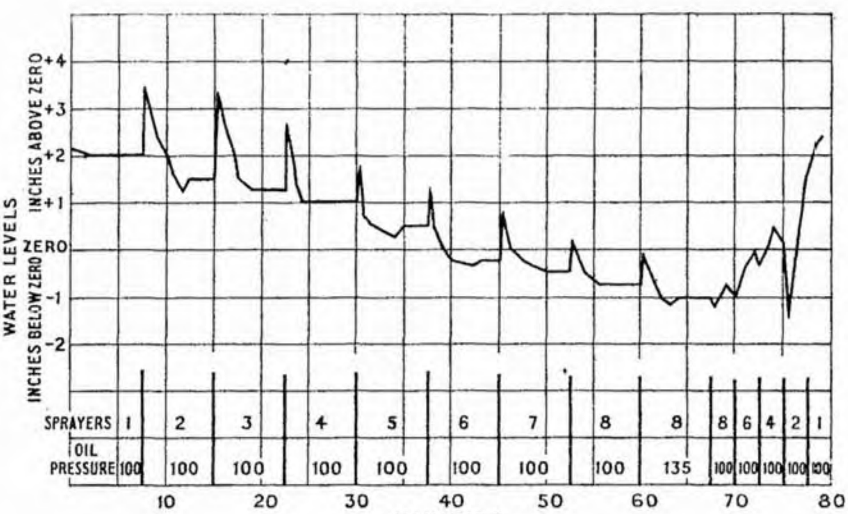


FIG. 19.

Test of Feed Regulator—Water-level Meaurements.

The greatest increase in level appeared to take place in this boiler when the third and fourth burners were put on. At the higher rates of evaporation the increase in level, as an additional burner is put on, becomes smaller, and it therefore becomes practicable on service to increase the rate of output of the boiler more quickly at high rates of evaporation than at low rates without danger of an undue rise in water-level.

On shutting off the burners the greatest fall in water-level takes place in this boiler changing from four to two burners, when the feed regulator is called upon to admit the feed-water at an exceptionally high rate. This is accounted for by the relatively great change in the density of the mixture circulating in the boiler at this stage as shown by the readings of the overall gauge given in Fig. 3.

It will be noted that the water-level in the boiler gauge glass is lower at high outputs than at low outputs. This has the effect of keeping the actual level of the mixture of steam and water in the steam drum at approximately the same height at all outputs. Since the density of the mixture decreases as the output of the boiler is increased, the height of the mixture in the steam drum above the level of the water in the gauge glass increases as the output is increased.

If, as is usual, the lower connection to the feed regulator float chamber is connected to the steam drum at a point below the lower connection of the water-gauge glass, the change in water-level from low powers to high powers will be greater in the float chamber than that shown in the water-gauge glass and so will give a larger movement of the float than that indicated by the change of level in the water gauge.

A number of automatic feed regulators have been tested by the method described and it has been found that very few are sufficiently steady in their action to meet the conditions without a measure of hand control.

Experiments were carried out with an old type of regulator which was originally fitted to the test boiler. This regulator gave an intermittent feed supply and it was reconstructed in order to give a more steady flow.

The results of tests shown in Figs. 18 and 19 were obtained with this regulator which has been in use for several years.

Number of Rows of Generator Tubes.—The effect of increasing the number of rows of generator tubes is to improve the efficiency of the boiler. This effect is relatively small at low outputs but increases at the higher outputs, with the result that in a boiler with a large number of generator tubes, the boiler efficiency does not fall as rapidly as the rate of evaporation is increased, as in the case of a boiler with a smaller number of rows.

This improvement is gained at the expense of increased weight of the boiler.

By reducing the size of the outer rows of tubes, *i.e.*, those situated on the side of the superheater remote from the furnace, from $1\frac{1}{8}$-in. diameter to 1-in. diameter, it was found possible to increase the number of rows of tubes with only a small increase in weight.

The splitting up of the stream of furnace gases as it passes through the tube nests into the larger number of gas passages when the smaller tubes are fitted, tends to improve the heat transmission and so add to the efficiency of the boiler.

Air Preheaters.—It has become the general practice to fit air preheaters where space is available. The space available for preheaters in warships is necessarily very small and limits the preheat obtainable to about 150° F.

The preheaters have proved to be satisfactory on service and give an increase in efficiency at all rates of evaporation, the results of trials showing that the increase in efficiency is fairly constant at all powers. This is of special value in a warship where a large proportion of the steaming is done at relatively low powers. Here again the increase in efficiency is obtained at the expense of an increase in weight and some increase in fan power to produce the increased air pressure required to overcome the resistance to the air and gases passing through the air heaters.

Experience has shown that the increase in weight and fan power is fully justified by the economies effected.

Efficiency curves for boilers with and without preheaters are shown in Fig. 20.

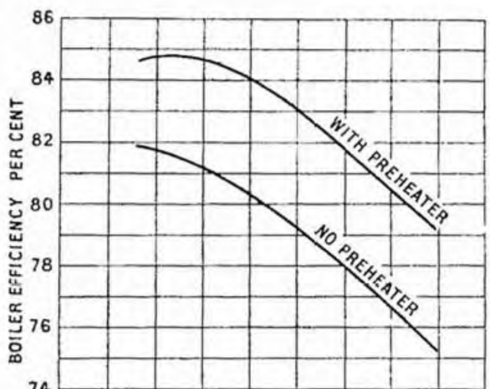


Fig. 20.

Curves of Boiler Efficiency.

Curves of Boiler Efficiency.—The curve of efficiency obtained on trials of a boiler fitted with the circulation augmentor is shown in Fig. 21, and the curve shown dotted indicates the estimated efficiency

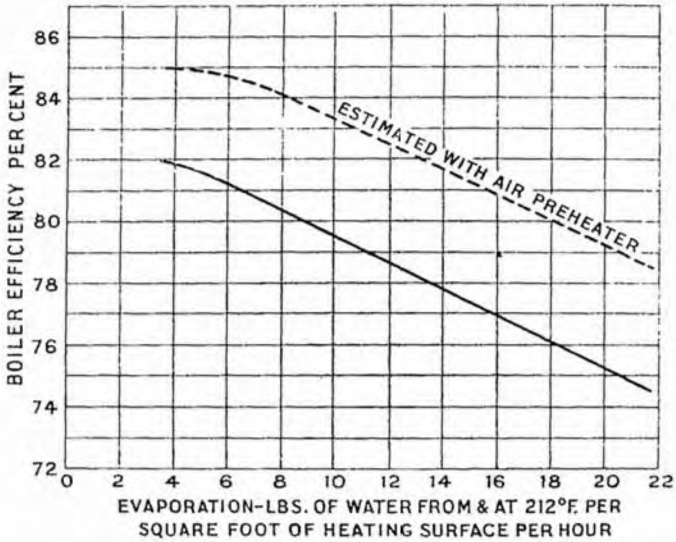


Fig. 21.

Boiler Efficiency with Circulation Augmentor Fitted.

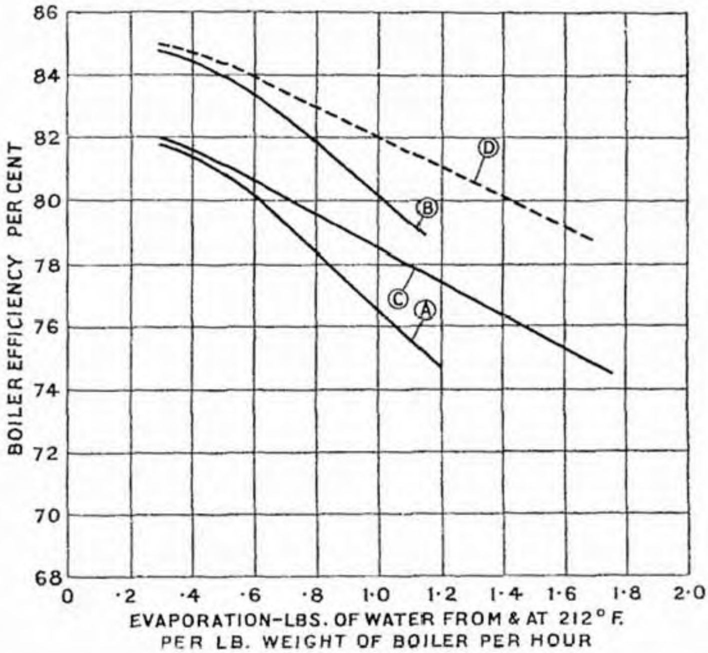
with an air preheater fitted. The boiler efficiency curves in Figs. 20 and 21 are plotted on a basis of rate of evaporation per sq. ft. of heating surface, and this basis has been generally used throughout this paper to denote the rate of forcing of the boiler. The heating surface referred to is the total heating surface including superheater surface in each case.

As it is nearly always possible to obtain an increase of boiler efficiency at the expense of an increase in weight of the boilers, a comparison of boilers on a weight basis is necessary in order to indicate more clearly the value of changes in design and type.

In Fig. 22, curves of efficiency of several three-drum type boilers are shown on a base of evaporation from and at 212° F. in lb. per hour per lb. weight of boiler. The boiler weight taken includes the weight of all boiler fittings, casings, brickwork, and air heaters, and water to working height.

These curves indicate that, while the total evaporation at maximum output with the normal boiler is 1·1 to 1·2 times the boiler weight, the output with the developments described is increased to 1·7 to 1·8 times the boiler weight for the same boiler efficiency at maximum output.

At one time the rate of forcing was limited by the amount of oil which could efficiently be burned in the furnaces, and the maximum was for some time about 12 lb. of oil per hour per cub. ft. of combustion chamber volume. With modern methods of oil burning this



Curve.	Particulars of Boiler Tubes.			Remarks.
	$1\frac{3}{4}$ in. Diameter.	$1\frac{1}{8}$ in. Diameter.	1 in. Diameter.	
A	2 rows	15 rows	—	
B	2 rows	15 rows	—	With air preheater
C	2 rows	3 rows	14 rows	With circulation augmentor
D	2 rows	3 rows	14 rows	With circulation augmentor and air preheater (estimated)

Fig. 22.

Boiler Efficiency and Output per lb. Weight of Boiler.

figure has been greatly increased, and on trials as much as 19 lb. of oil per cub. ft. of combustion chamber volume has been satisfactorily burned.

The water-tube boiler with natural circulation has now been in use in warships for moderate steam pressures for many years and in its present form, is the result of years of experience and development, to which a large number of engineers, designers, and manufacturers have contributed. It has proved to be very reliable and gives a large steam output for a relatively small weight and space.

The arrangements described for providing it with a guided circulation increase its output for the same weight and space to a somewhat greater extent.

The application of a forced circulation to the water-tube boiler, in order to reduce its size and weight still further, has been the subject of experimental work and development for many years, and the successful use on shore and afloat of water-tube boilers with forced circulation makes it appear probable that the water-tube boiler now in general use may eventually be displaced to a great extent by the boilers with forced circulation, in much the same way that the cylindrical boiler was displaced by the water-tube boiler.

The application of this type of boiler for naval work is receiving attention, having due regard to the efficiency, reliability, weight, and space occupied; we have, for example, at the present moment under trial a "Velox" boiler which has a forced circulation of the water and steam, together with a highly forced circulation of the furnace gases.

Appendix.

Pitot-Tube Apparatus.—The Pitot tube was inserted in the lower end of one of the generating tubes of the boiler and connected to an indicator by small pipes led through the shell of the water drum.

The Pitot tubes were of very small diameter and, although their presence caused a local restriction in the clear area through the boiler tubes in which they were inserted, the restriction was only of the order of 7 per cent. in the case of the fire-row tubes and 12 per cent. in the outer rows of tubes. It is realized that the velocity of circulation through the generator tube in which the Pitot tube was fitted would be affected by the restriction thus caused, but it is considered that the readings gave a reasonable indication of the circulation conditions.

The indicator for the Pitot-tube apparatus consisted of two parallel glass water gauges connected at their lower ends to the leads from the Pitot tube. The upper ends of the water gauges were connected, and a small screw pump was fitted to the top connection by which oil could be pumped into the upper parts of the water gauges. The oil used was of specific gravity of 0·8, and the velocity-head readings, indicated by the difference in level in the two gauges, in inches, were therefore five times the actual velocity head in inches of water. By pumping more oil into the apparatus, thereby displacing water through the leads, errors due to choking or steam in the tubes could be detected by the change in the reading of the instrument.

The apparatus was calibrated by fitting it in a tube exactly similar to the boiler tube and providing a flow of water through the tube into a measuring tank.

The readings of the indicator and the actual flow through the tube were noted at different rates of flow.

Circulation in Boiler.—A diagrammatic arrangement of a fire-row tube and an outer-row tube is shown in Fig. 23.

v_1 is the velocity at entry to the fire-row tube and v_2 the velocity at the upper or discharge end, d the density at the top of the outer-row tube, d_1 the density at the bottom of that tube and at entry to the fire-row tube, and d_2 the density at the upper end of the fire-row tube, H is the height of the tubes.

The head producing circulation will be the difference in head in the two tubes.

Assuming the mean density in each tube to be the mean between the densities at the inlet and outlet, the head causing circulation will be

$$H\left(\frac{d+d_1}{2}\right) - H\left(\frac{d_1+d_2}{2}\right) = H\left(\frac{d-d_2}{2}\right)$$

The kinetic energy of the mixture leaving the upper end of the fire-row tube $= \frac{d_2 v_2^2}{2g}$.

Neglecting frictional effects and the losses on entry and exit

$$\frac{d_2 v_2^2}{2g} = H\left(\frac{d-d_2}{2}\right)$$

$$\therefore \quad v_2^2 = gH\left(\frac{d-d_2}{d_2}\right)$$

The mass flow in the fire-row tube $= Av_2d_2$, where A = area of the tube

$$\therefore \quad \text{Mass flow} = Ad_2\sqrt{gH\left(\frac{d-d_2}{d_2}\right)}.$$

If the ratio between the densities d and d_2 is R, then $d_2 = \frac{d}{R}$.

The mass flow becomes $\frac{Ad}{R}\sqrt{gH(R-1)} = Ad\sqrt{gH} \times \frac{\sqrt{R-1}}{R}$

From this it appears that the mass flow will vary directly as the density of the mixture in the steam drum and will also vary with the function $\frac{\sqrt{R-1}}{R}$.

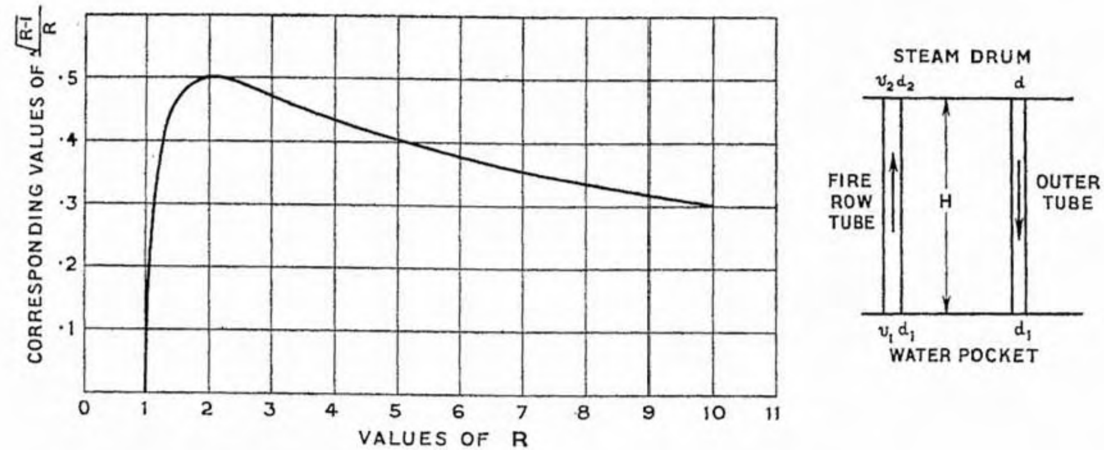

CORRESPONDING VALUES OF $\frac{\sqrt{R-1}}{R}$
·5
·4
·3
·2
·1
0 1 2 3 4 5 6 7 8 9 10 11
VALUES OF R
STEAM DRUM
v_2 d_2
d
FIRE ROW TUBE
H
OUTER TUBE
v_1 d_1
d_1
WATER POCKET

Fig. 23.

The values of $\frac{\sqrt{R-1}}{R}$ for different values of R are shown plotted in Fig. 23, and its value increases with increase of R until R equals 2 and decreases as the value of R is increased beyond this amount.

The value of R would increase as the rate of evaporation increases and more steam is generated in the fire-row tubes, and it therefore appears that the mass flow in a fire-row tube may be expected to increase as the rate of evaporation is increased at low outputs, and to decrease as the rate of evaporation is increased at high outputs.