MAIN CIRCULATING SYSTEMS

BY

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Introduction

The estimation of pump duty, the general requirements of a pump and the design of the associated pipe system should always be a matter for careful consideration if efficient and trouble-free pumping is to result. Faulty selection of pump duty and poor design of pipe systems will lead to inefficient operation, wear and erosion of both pump and pipes, and to much undesirable noise.

Thus in a main circulating system, which is the largest pumping system in H.M. ships, very careful consideration must be given to pump design and duty, and to the design of the system. In H.M.S. *Ark Royal* the main circulator output is 32,500 gallons per minute or about 9,000 tons per hour. The purpose

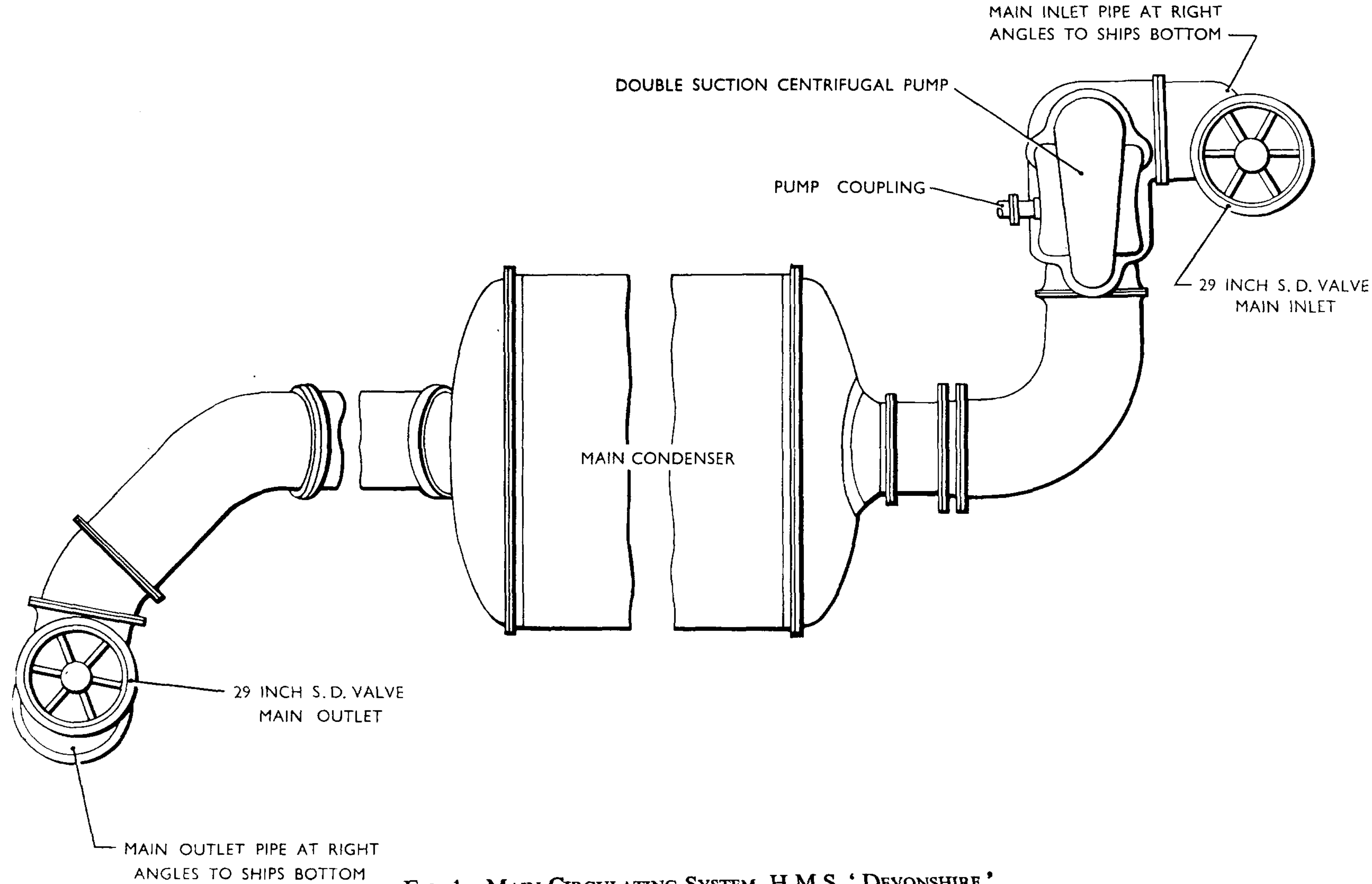

FIG. 1—MAIN CIRCULATING SYSTEM, H.M.S. 'DEVONSHIRE'

of this article is to outline the design of a modern main circulating system and to show the improvements obtained in the last twenty-five years.

The original calculation of main circulator duty is closely concerned with the design of the condenser. Increasing the water velocity gives an increased heat transmission from the tubes to the condensing steam. For a given surface area of tubes a higher condenser efficiency can be obtained by fitting a small number of long tubes. Obviously this cannot be carried beyond certain limits on account of the space required and because of the increased resistance to flow. The length of the condenser could be reduced by arranging the water circuit in two or more passes, but, as the resistance to flow depends partly on inlet and outlet losses at the tube ends, this involves a further increase in pumping power.

Thus the choice, in practice, lies between using a large quantity of water and a relatively small surface and a much smaller quantity of water and a larger surface. As an example the same cooling effect is obtained by condensers (*a*) and (*b*) below :—

Condenser (*a*) Tubes 5 feet long
Surface area 24·2 units
Cooling water 12·5 units.

Condenser (*b*) Tubes 25 feet long
Surface area 36·7 units
Cooling water 3·7 units.

As there is ample water available from the sea, the decision rests mainly upon the balance between the weight of the condensing plant and that of the whole installation as influenced by the power of the circulating pump, taking into account its steam consumption.

In most geared steam turbine designs it has been necessary, in order to use the available space to the best advantage, to fit the condenser below the turbine. This somewhat limits their size and shape and hence the tube length, which averages 10–13 feet in moderate and high-powered designs and less in low-powered designs.

In early main circulating systems, inlet scoops had not been developed, with the result that large centrifugal pumps operating continuously at substantial powers had to be used. With the careful design of every part of the system and with the introduction of inlet scoops, the power of the pumps necessary has been much reduced. In many classes of ship the scoop effect provides all the pumping action necessary under most steaming conditions and the main circulators are only required to ' trail ', or they may be fitted with a ' free-wheel ' as in the steam gunboats.

Three systems typical of old, improved and latest practice are shown in FIGS. 1, 2 and 3. FIG. 1 shows the arrangement in the County Class cruisers where the sea suction was a tube at right angles to the ship's bottom. A centrifugal pump provided the total pump head of 30 feet which was necessary to provide the required flow through the condenser tubes (7 feet per second). In the arrangement for the Emergency Class destroyers, an inlet, set at about 30 degrees to the ship's bottom, was incorporated in the system (FIG. 2). In an attempt to produce a water path having minimum resistance to flow a rather long and bulky installation was produced. The convergent-divergent form of the opening led to severe eddying and consequent erosion.

In the steam gunboat, and later in the Weapon Class destroyers, the inlet had a throat at entry and then a diffusing portion to ensure that the velocity

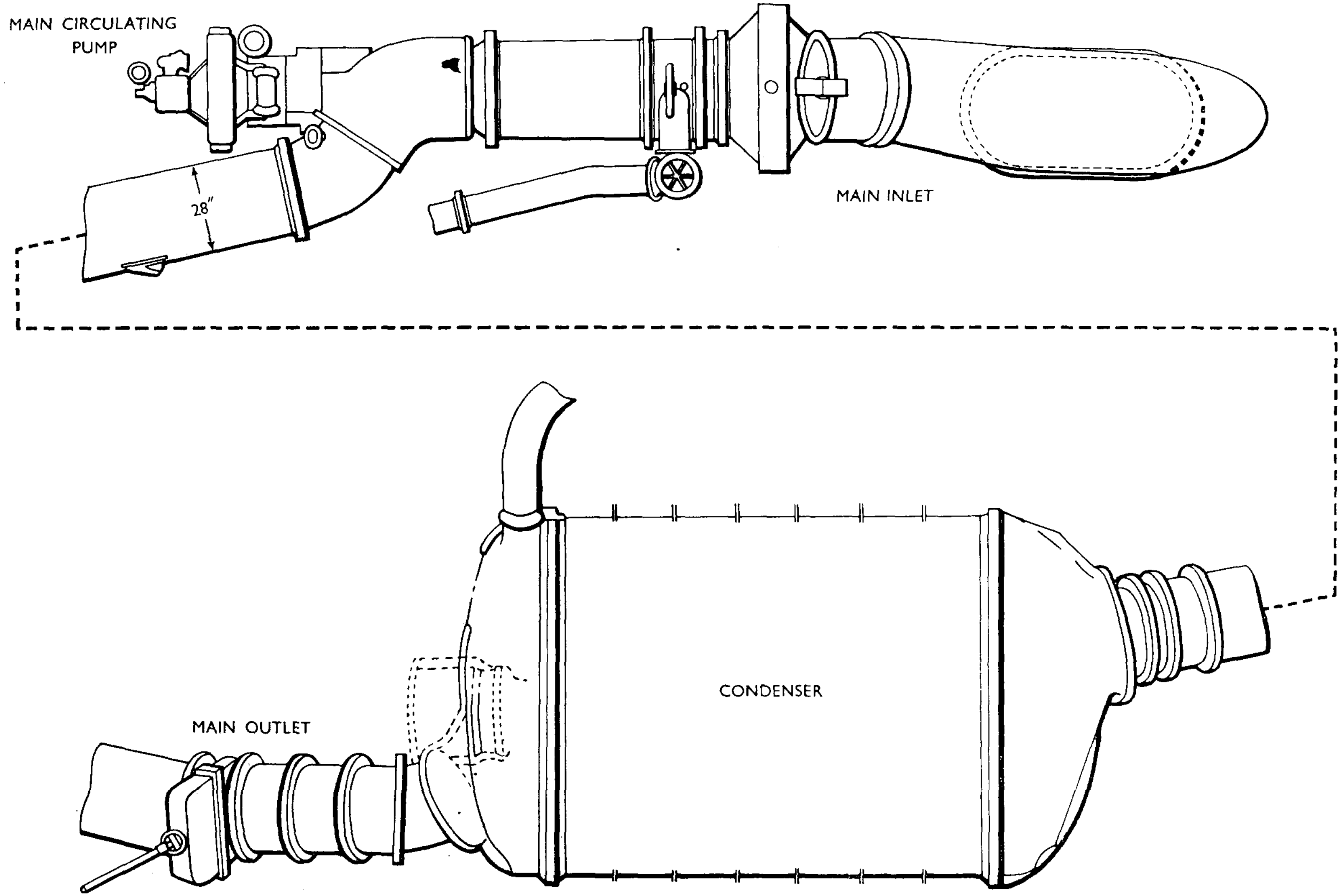

FIG. 2—MAIN CIRCULATING SYSTEM, H.M.S. 'ZODIAC'

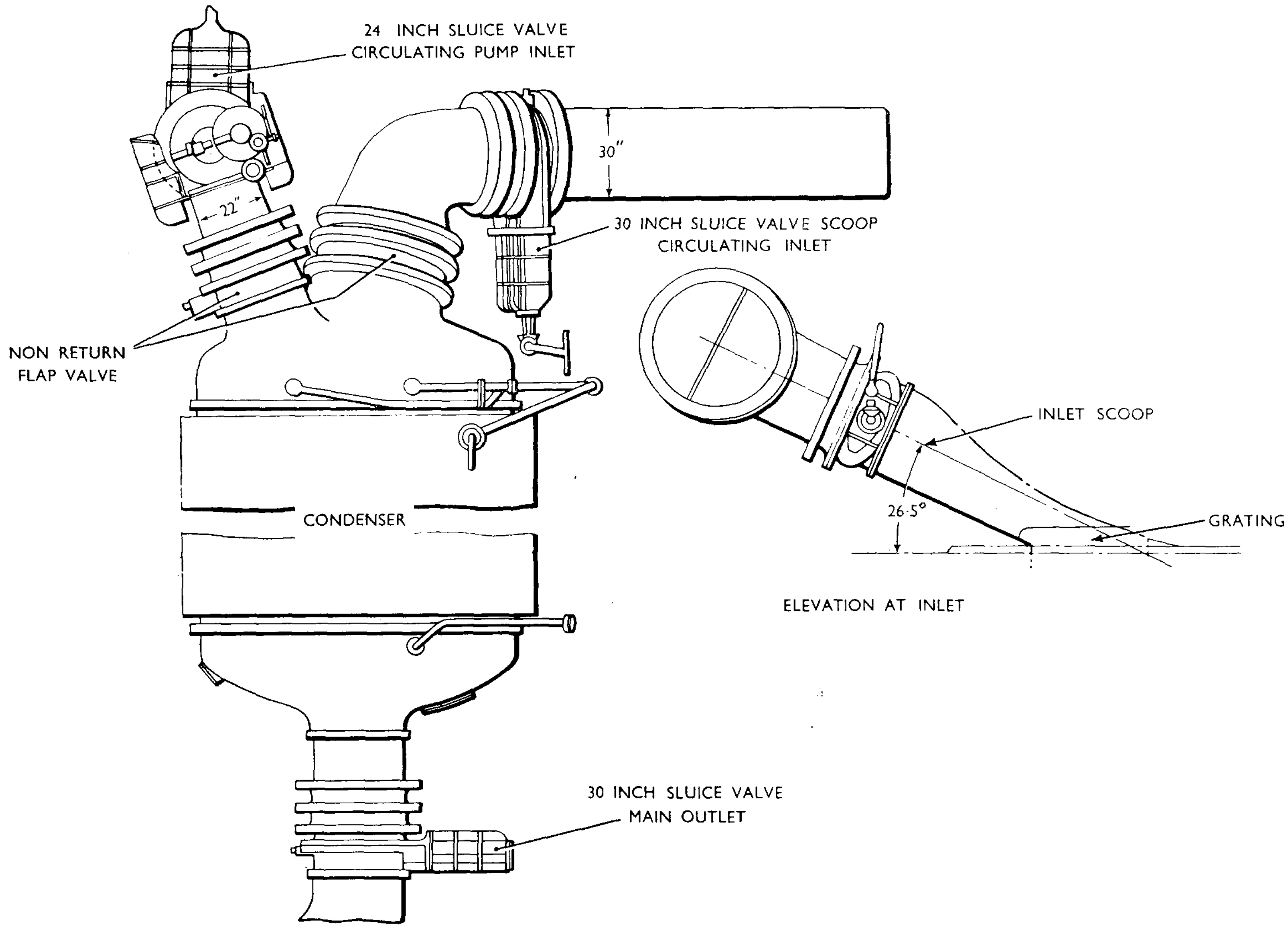

FIG. 3—MAIN CIRCULATING SYSTEM, H.M.S. 'DARING'

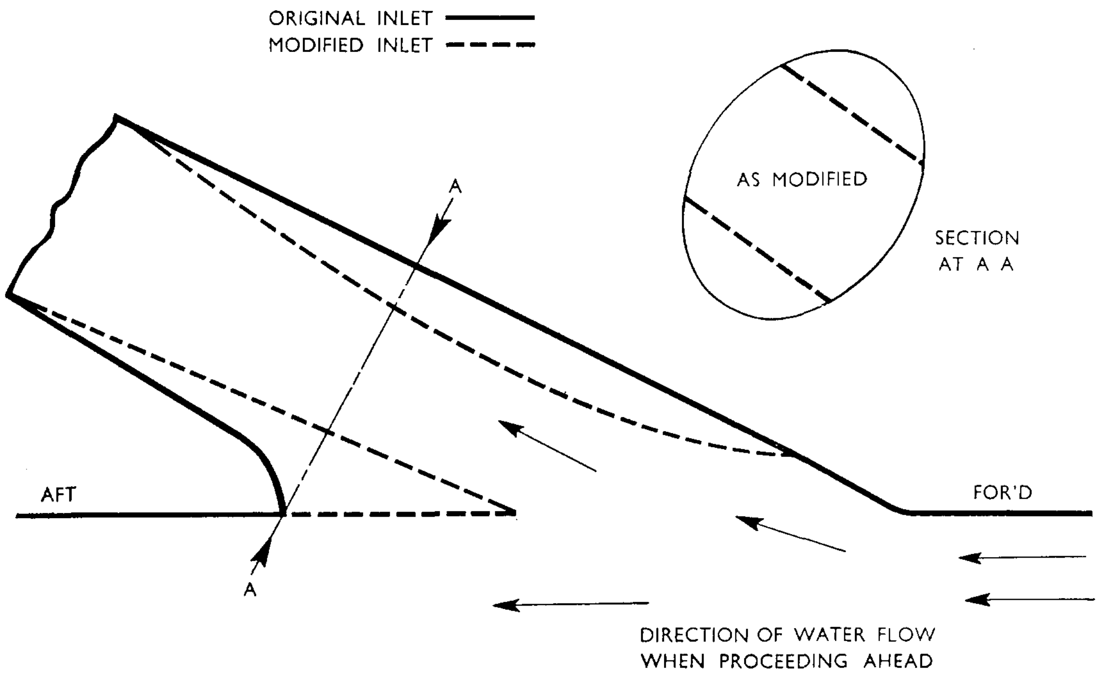

FIG. 4—MODIFICATION TO MAIN INLET, H.M.S. 'ZODIAC'

energy in the water flow past the ship was not wasted in eddies. In order to suit the staggered arrangement of machinery in these ships, and in the *Daring* Class, the condenser tubes lie athwartships, resulting in a neat arrangement for both condenser and inlet pipes. The design of the turbine bearers is simplified, and the piercing of main bulkheads by large inlet pipes can be avoided.

In the *Daring* Class as in most ships of United States Navy, there is both an inclined entry for normal ahead steaming, relying entirely on the energy of the incoming water to overcome the losses in the circulating system, and an entry perpendicular to the hull surface through which the circulating pump, for use when manœuvring, takes suction. A butterfly valve prevents re-circulation between the two inlets. In the *Darings* a speed of 7 feet per second through the tubes at full power is produced by this arrangement. It is understood that by improvements in design the United States Navy has now achieved a speed of 9 feet per second by this means.

The design of inlet scoops, outlet arrangements, etc., is a difficult procedure as little detailed information on systems in use is available. However research has been proceeding, both on models and in actual ships on various parts of the system, but the work is by no means complete. Ship trials, model results and theory have not been completely reconciled to each other so far because there is a considerable scale effect, but a reasonable measure of agreement has been obtained. Attempts are being made to correlate results so that, in future work, model experiments and the theories available will give a reliable and accurate indication of the characteristics of a new full-size installation.

System Resistance

As both the inlet and discharge are below the water-line the circulating pump does not have to lift the water in the system considered as a whole. The resistance to flow depends, therefore, only on the velocity of the water in the system and upon the arrangement of the condenser, pump, valves, pipes and other fittings. In view of the large quantities of water, and hence power, that are being dealt with it is important that every effort should be made to reduce the resistance of every item in the system to a minimum.

The system may be considered in the following parts :—

(*a*) Main inlet
(*b*) Circulating pipes and fittings
(*c*) Inlet to, and flow through, the condenser
(*d*) Outlet scoop and lip, etc.

Main Inlet Design

The inlet is inclined to some 30 degrees to the ship's bottom and the designer's object is to ensure that the water flowing into it suffers the least disturbance to flow. Immediately following the inlet throat there is a diffusing section to convert the velocity energy of the water to pressure energy on reduction of its speed to that in the inboard system.

Sufficient head of water is created in the inlet pipe to force the water through the circulating system. The resistance of the system rises as the flow increases. It can be shown that the calculated and measured resistance heads are appreciably different. The measured head also seems to differ by up to 20 per cent between identical installations, for no apparent reasons. Thus any calculations made should take into account the possibility of such discrepancies.

The advantages that can be obtained by a well-designed inlet were demonstrated by trials carried out in H.M.S. *Zodiac*, where modifying the inlet as shown in FIG. 4 increased the available head by 20 per cent and the flow by 10 per cent. Details of this work were described in an article in the *Journal* (Vol. 5, No. 3) entitled ' An Investigation into the Loss of Condenser Vacuum in Emergency Class destroyers '.

The main inlet should be fitted with a grating offering the least resistance to flow. These are often fitted as thin bars of aerofoil section.

Model tests have been carried out to determine the best shape of an inlet scoop and the effect of varying the angle of the inlet to the ship's bottom. These tests indicate that 20 degrees is the most efficient inlet angle, but up to 30 or 35 degrees has been used in some inlets as small angles tend to weaken the ship's structure due to the length of the hole in the ship's bottom. With regard to the configuration of the inlet a number of conclusions have been drawn, as described briefly below. Definitions of the various terms used are given in FIG. 5.

(*a*) The value of a projecting inlet lip is doubtful. In the case of a circular inlet it is detrimental, but a rectangular sectional inlet benefits slightly from a small lip and markedly from a large one.

(*b*) With scoops of approximately square section, splitters are beneficial only in low ranges of flow. In higher ranges they are detrimental.

(*c*) High expansion ratios produce high heads at relatively low flows but ' choke ' at higher flows, 1·6 appearing to be the highest reasonable figure.

(*d*) The best practical aspect ratio appears to be about 2. Figures of this order, however, are undesirable from the ship construction point of view as explained above.

(*e*) The effect of the radius ratio is not marked, except in that it affects the angle made by the forward wall of the scoop with the shell.

(*f*) The cause of breakdown in scoop performance at high flow is the breakaway, due to separation, that occurs on the forward wall of the inlet.

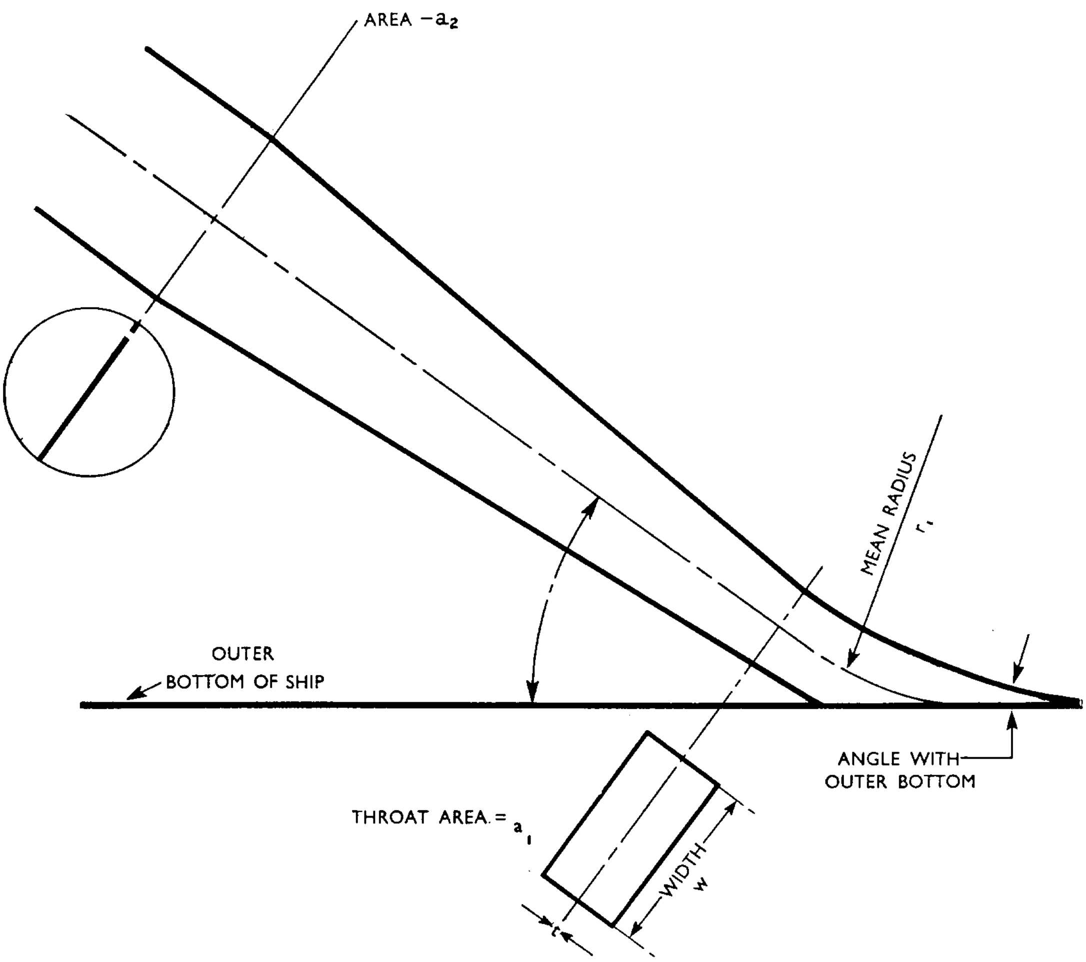

FIG. 5—INLET TERMINOLOGY

Expansion ratio $: \frac{a_2}{a_1}$ Aspect ratio $: \frac{w}{t}$ Radius ratio $: \frac{r_1}{t}$

This is confirmed by ship tests.

(*g*) When going astern, any improvements in the design of the scoop for ahead operation results in a corresponding increase in the circulating power necessary when going astern. This is also confirmed by ship tests. Early tests also showed that the flow, just before entry, has an athwartships component as well as those in the fore and aft and in the vertical directions as shown in FIG. 6. To avoid eddies, the trough in the hull outside the throat should have flaring sides with rounded edges and a narrow tulip shape.

Circulating Water Pipes and Fittings

In order to keep the resistance in the pipes and fittings to a minimum, it is essential that the water velocity should be low, although unduly low velocity leads to large pipes and increased weight. A maximum velocity of about 10–12 feet per second is allowed in large ships and somewhat higher speeds in destroyers where the leads are short and direct. The length of the circulating water pipes is kept as short as possible. The improvement obtained in recent years is shown by comparing FIGS. 2 and 3. Abrupt changes in direction of flow and obstruction in flow are avoided as far as possible. Any changes in section

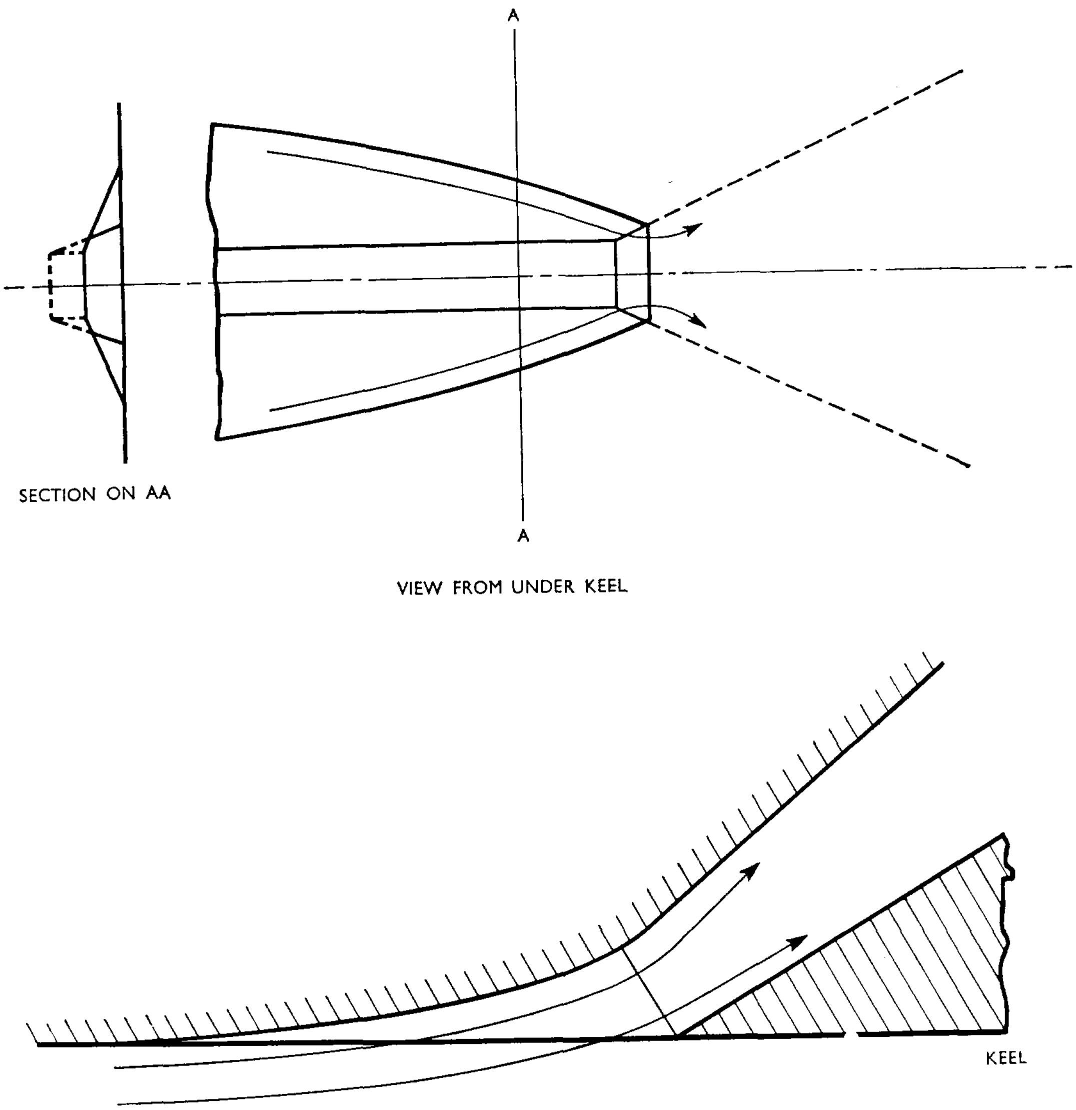

FIG. 6—FLOW IN THREE PLANES

necessary in way of the main inlet and outlet valves and other fittings, such as weed traps, are made by gradual changes of direction and area.

Inlet To and Flow Through the Condenser

The inlet cover of direct flow designs require special consideration to ensure that the water is uniformly distributed to all parts of the tube plate. Thus the inlet cover is made as deep as space will allow to permit the velocity change to be made gradually and to avoid eddy losses as far as possible. In power stations, tubes of $\frac{3}{4}$ to 1 inch diameter are used, the larger size being used in large condensers and where there is sediment in the water. In the Merchant Navy $\frac{3}{4}$-inch tubes are used, but in the Royal Navy considerations of weight and space have led to a standard diameter of $\frac{5}{8}$-inch.

As shown above the heat transfer rate depends on the water velocity through the tubes. Until recently, 7 feet per second was found to be the highest speed which could be used without undue erosion occurring, but in the latest designs, 10 feet per second is being used and higher speeds are being contemplated.

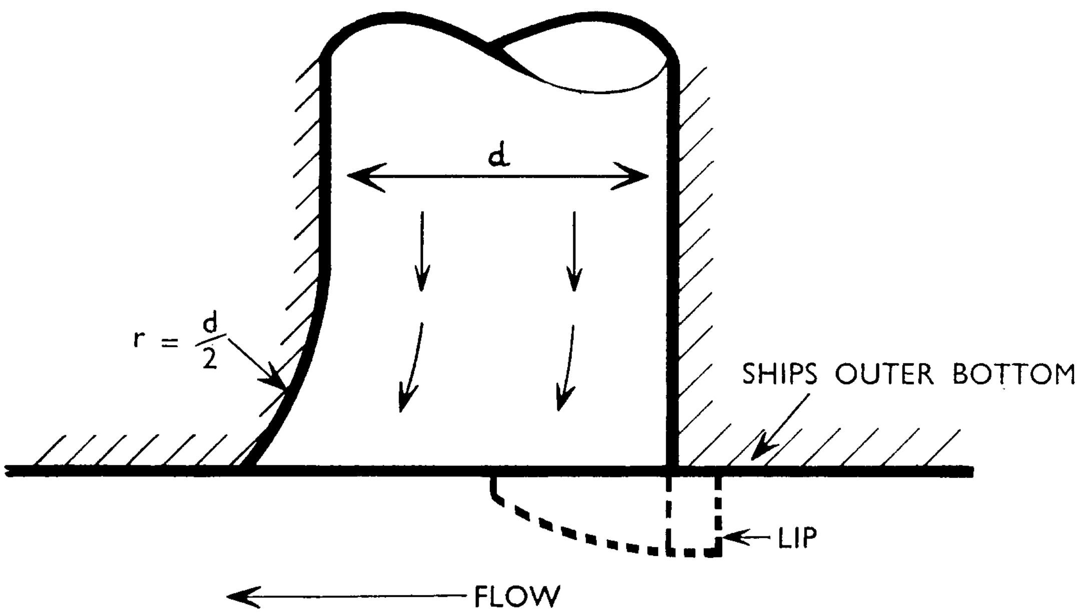

FIG. 7—OUTLET CONFIGURATION

The friction loss on the water side of a condenser can be expressed as :—

$$H = n \left[C_1 \frac{L. V_t^2}{2gD} + C_2 \frac{V_t^2}{2g} \right] + C_b \frac{V_b^2}{2g}$$

where n = No. of passes
L = length of tube in feet
D = diameter of tube in feet
V_t = mean velocity of water through tubes in feet/sec.
V_b = velocity in outlet branches in feet/sec.

In this expression the first term represents the loss in the tube itself, the second, the loss at entry and exit of the tube, and the third, the loss in the water box and pipes. The coefficients C are derived from experimental curves. The value depends on the type of end fixing employed. For $\frac{5}{8}$-inch tubes with Crane packing a value of 1·1 may be used. With well designed water boxes and a fair lead of piping C_b may be taken as 1·0, but this factor does not include the loss of head in the pump itself or in the inlet and outlet valves. If leads are indirect or have sharp bends C_b will be considerably increased. Some increase in total head must also be allowed for dirty tubes.

Using the formula above for water velocities through the tubes of 7, 10 and 15 feet per sec. respectively, the loss of head due to flow through the tubes and at inlet and outlet is :—

Water velocity	feet per sec.	7	10	15
Loss through tubes	feet	4·4	7·2	17·6
Loss at inlet and outlet	feet	0·9	1·7	3·9

Outlet Design

The exit angle for main outlets is nearly always over 45 degrees and is often at right angles to the ship's bottom or side. Lips, as shown in FIG. 7, fitted to the upstream side of the outlet substantially increase the suction on the outlet. Sea trials in H.M.S. *Zodiac* have confirmed this.

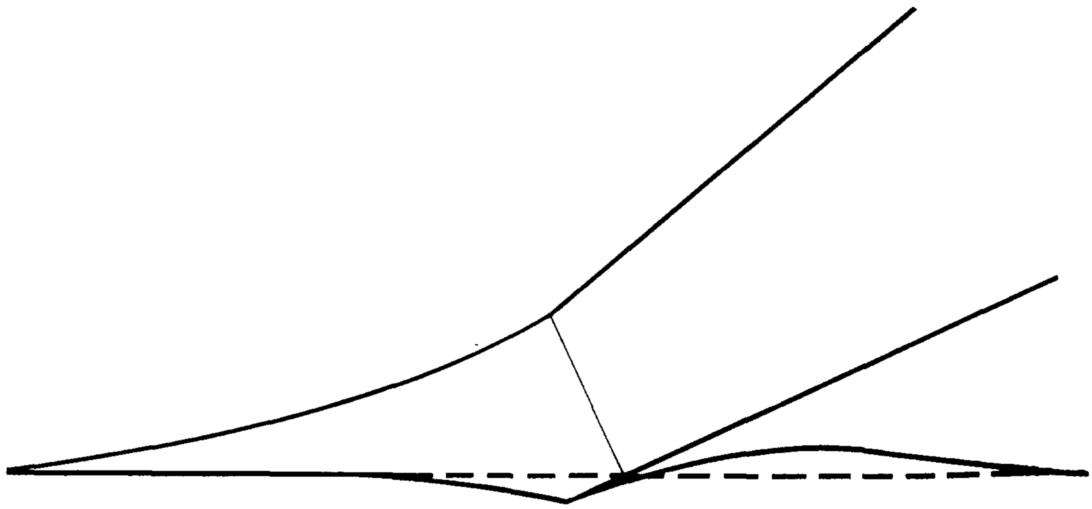

FIG. 8—' MARINER ' CLASS OUTLET

Model tests have shown that :—

(*a*) Suction in a 90 degree outlet varies roughly as the square root of the height of the lip.

(*b*) For equal projection from the ship's bottom, more suction is developed by a perpendicular lip than by a sloping one.

(*c*) If a main outlet retards the flow of water through the system a lip is fitted. A lip does not increase the flow at normal outputs unless the lip height is greater than about 12 per cent of the pipe diameter.

(*d*) The most efficient shape of lip is shown in FIG. 7.

(*e*) A radius between the after wall of the outlet and the ship's outer bottom increases the suction in the outlet at normal outputs, whether a lip is used or not.

(*f*) A 90 degree lipless outlet with a fillet radius equal to half the pipe diameter is as effective as a sloping lipless outlet. This is shown in FIG. 7 and can also be seen in the *Daring* Class outlet in FIG. 3.

In the *Mariner* Class minesweepers the outlet is as shown in FIG. 8.

Trials have been carried out in a ship with projecting lips on the forward side of outlets which give a substantially increased suction at the cost of slight increase in ship resistance. Their use is tempting to the circulating system designer but from the overall ship point of view the best design of inlet and of outlet is one which gives minimum disturbance to the flow round the hull and minimum eddy loss in the inlets and outlets.

Main Circulating Pumps

In early designs of ships, the main circulating pumps were always of a centrifugal type. The change-over to axial-flow pumps was made during the nineteen-thirties, although small ships still use centrifugal pumps. The low speed of axial-flow pumps results in geared turbines. Some of the latest designs use a compact epicyclic gearing which produces a neat unit with the turbine and pump shafts in line.

As a result of the use of scoops, the maximum output required of a circulator

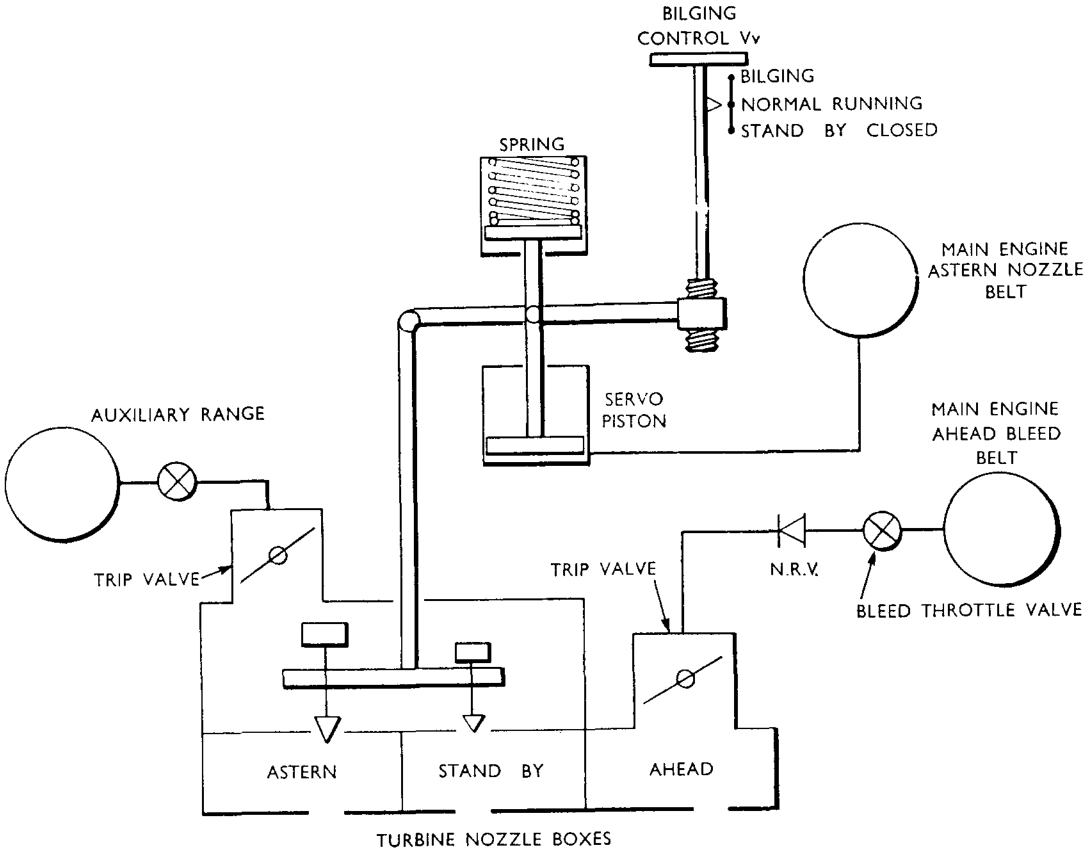

FIG. 9—MAIN CIRCULATOR AUTO CONTROL SYSTEM (DIAGRAMMATIC)

Running Conditions : Arctic-stand-by nozzle closed and, or bleed-valve throttle closed

Temperate: } stand-by nozzle open
Tropic : }

is during the full astern condition. As this is not a continuous requirement, it can be met by an overload rating for the turbine.

The correct pump speed for 'trailing' at any ship speed can be found by altering the pump speed slowly and observing closely some point on the pump shaft, such as the coupling or a screamer gauge. The 'trailing' speed is that at which the pump shaft moves axially as the direction of thrust on the shaft changes and the thrust collar moves from one set of thrust pads to the other.

Main Circulator Control

Circulators are normally controlled by a conventional stop valve, extra nozzles being opened if necessary at high powers, when going astern, or when operating in tropical waters. Until recently the stop valve has been hand operated by a watchkeeper. In order to meet modern requirements for remote control of machinery, a recent design incorporates automatic speed control. The arrangement is shown in FIG. 9.

There are three sets of nozzles, ahead, astern and stand-by. The ahead nozzles are supplied with steam from a bleed-belt in the main H.P. turbine. They pass steam whenever the ahead main engine throttle is open. Thus the higher the main engine speed, the more steam passes to the circulator turbine ahead nozzles.

The astern and stand by nozzles are supplied with steam from the auxiliary range. The nozzle valves are controlled either by a handwheel or by a servo-cylinder supplied with steam from the main engine astern nozzle belt. Astern steam in the servo-cylinder is balanced against a spring. When the main engine astern throttle is open the servo-cylinder moves upwards against the spring, opening the astern nozzles fully. The bilging control valve can also open the astern nozzles when the circulator is required to run at full speed on bilge suction.

The stand-by nozzles can also be controlled by the bilging control valve to adjust circulator output for varying sea temperature though, normally, control of the circulator would be obtained by means of the bleed-valve.

Boost Pump or Natural Flow

In many high speed ships in the United States Navy and in the *Daring* Class the flow through the condenser at all normal ahead speeds depends only on the ship speed through the water, the circulating pump being stopped. If the condenser is adequate for the mean world sea temperature of 70 degrees, the vacuum will fall a little below optimum in the tropics. In cold waters there was an initial fear of under-cooling at low powers, but as the steam flow in oversize condensers at reduced powers often limits itself to a portion of the steam lane only, this may explain why under-cooling has not actually been experienced.

At full power the water speed through the condensers in the *Daring* Class is 7 feet per second. From consideration of safe tube life it is possible to increase this to 10 feet per second with a consequent reduction in condenser surface and weight. The top speed of the *Blackwood* Class frigates is appreciably less than the *Darings*. Thus, fitting a circulating pump in the main line for ahead running enables a top speed of 10 feet per second through the tubes to be used.

The penalty is :—

(*a*) The increased resistance to flow due to the pump
(*b*) The weight of the pump
(*c*) The steam consumption of the pump.

The latter is of moment only in the tropics, but it entails carrying additional fuel.

On balance, therefore, it appears that the natural flow scheme will be applicable to fast, heavy ships where machinery weight is a smaller proportion of hull weight and where fuel weight is more than machinery weight. The boost pump scheme will show to advantage in small, slower ships when the machinery is a high proportion of the hull weight. It may be important in certain installations to eliminate the noise made by the pump.

References :

(i) Information has been obtained from reports of sea trials carried out in H.M. ships, from reports on model experiments carried out at the A.E.W., and from discussions in E.-in-C. (Bath).

(ii) *Condenser Scoop Design* by Hewins and Reilly : *Society of Naval Architects* and *Society of Marine Engineers*, 1940.