HIGH DUTY AIR COMPRESSORS.

For many years high-duty air compressors have formed part of the necessary equipment for warships, principally for armament purposes, and clearly defined progress has been made in such machines as their use has been extended and also the maximum pressures required have increased. Due to the physical differences between air and water, the compression to high pressures of the former medium has involved the overcoming of certain mechanical and thermal difficulties that do not arise in hydraulic machines, and even at the present time air compressors are units that require very careful design and attention if the desired reliability and efficiency are to be obtained. In recent years the development of the internal combustion engine and its application as the prime mover for many classes of ships apart from auxiliary purposes, and also for shore power stations, has led to a more general study of the problems of air compression since such units in connection with the oil engines are required to work under more arduous conditions than those associated with the armament in warships. While the reliability of air compressors when fitted for armament purposes is of first importance, their use is of an intermittent nature, and ample facilities therefore, exist to enable their upkeep being sufficiently assured in a light design. Quite different is the question when such units form an integral part of an internal combustion engine using air-injection, for the working of the power portion of the engine is entirely dependent on the satisfactory performance of the compressors, and moreover such compressors are in continuous use.

Even in the cases of internal combustion engines using solid injection, compressors are necessary to supply the air for starting and manœuvring purposes, so that in any case the movements and safety of a ship fitted with I.C. engines is dependent on the efficiency and reliability of the air compressors no less than on those of the main engines. That such is recognised is borne out by the rules governing the installation of Diesel engines in merchant ships under Lloyd's Register and in which it is laid down that auxiliary compressors are to be carried which will have the same capacity as those that form an integral part of the main power unit and which compressors can supply not only the air necessary for injection purposes, but also the margin required for maintaining charged the starting reservoirs under the manœuvring conditions to be ordinarily anticipated. The mere fact that such compressors have to be suitable for efficient running when supplying injection air only and yet possess capacity for charging the starting reservoirs in addition has in itself led to certain difficulties which will be referred to later. It can be appreciated, therefore, that with the widespread adoption of the internal combustion engine the development of suitable compressors to meet the arduous conditions should have considerably progressed in recent

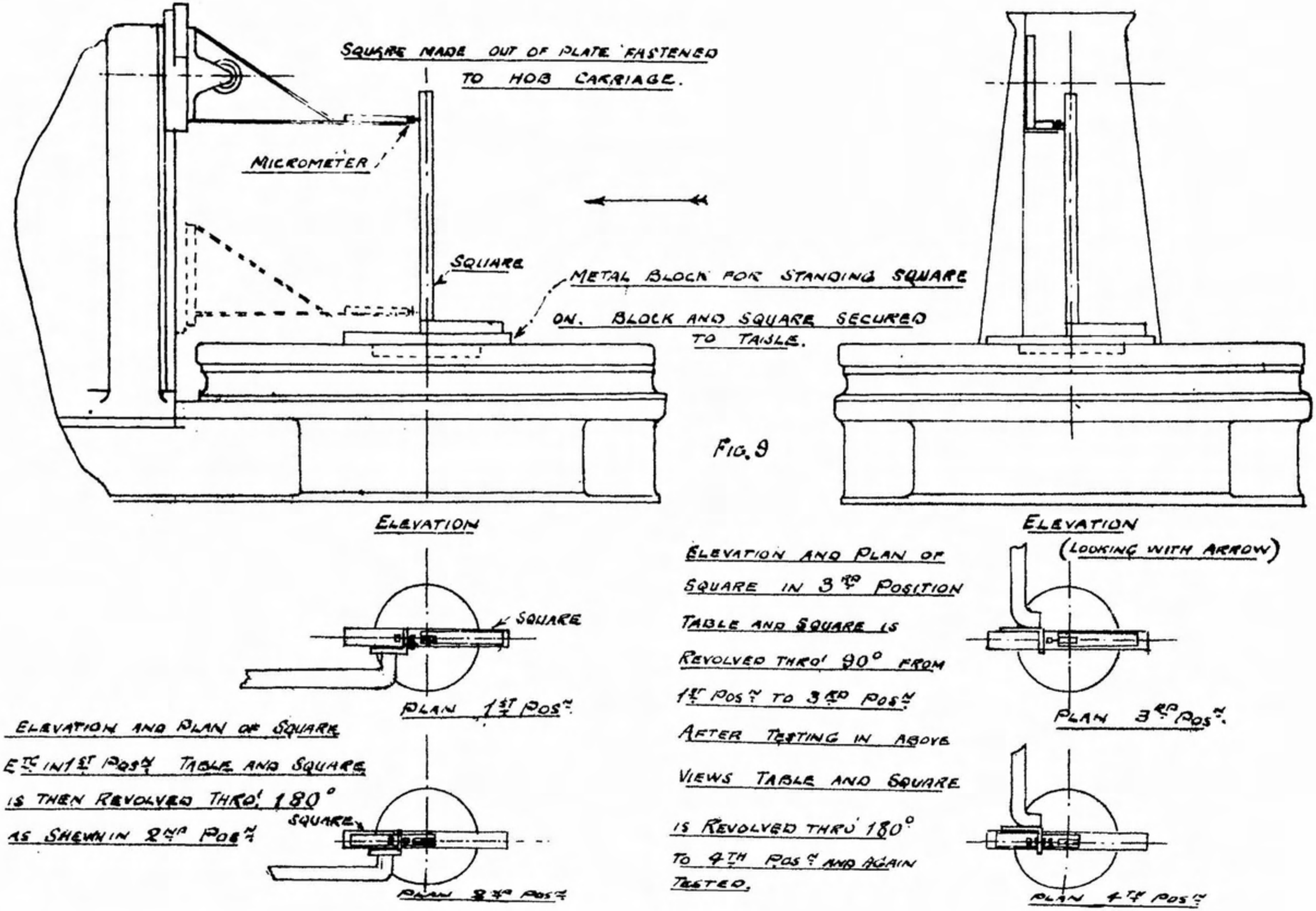
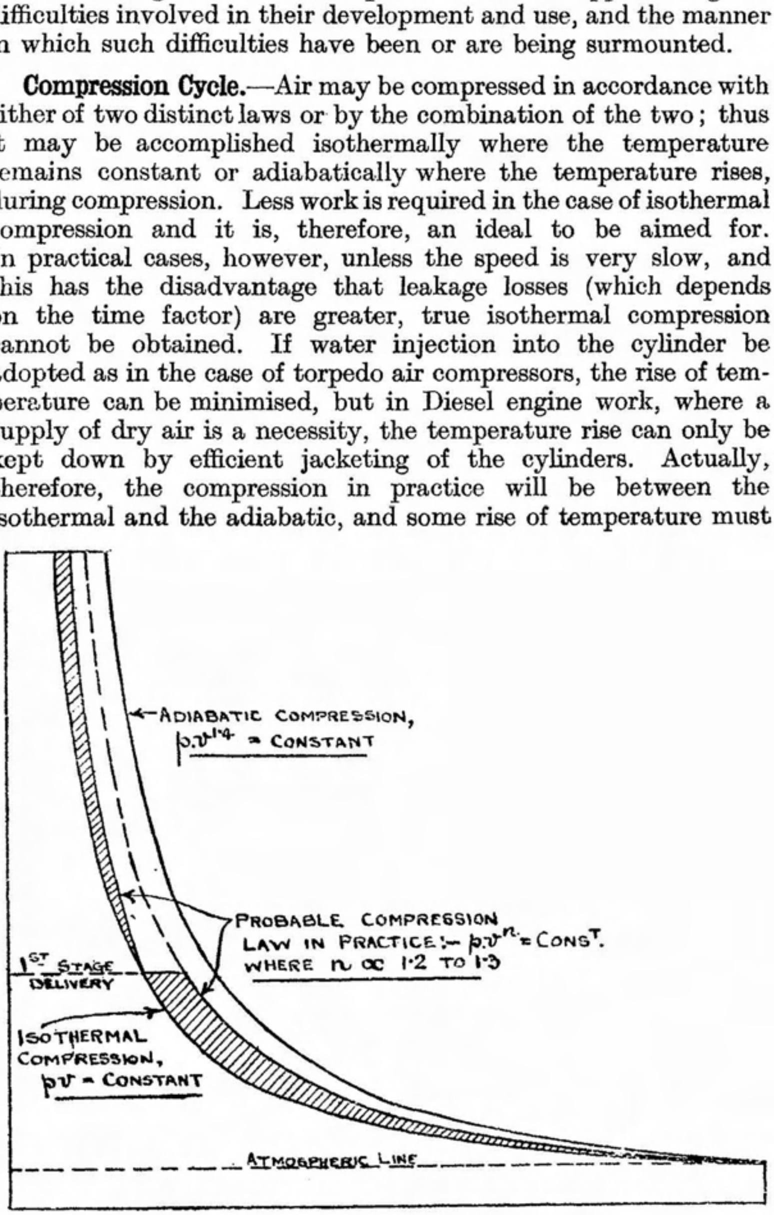

SQUARE MADE OUT OF PLATE FASTENED TO HOB CARRIAGE.
MICROMETER
SQUARE
METAL BLOCK FOR STANDING SQUARE ON. BLOCK AND SQUARE SECURED TO TABLE.
ELEVATION
ELEVATION
(LOOKING WITH ARROW)
SQUARE
PLAN 1ST POSN.
ELEVATION AND PLAN OF SQUARE ETC IN 1ST POSN. TABLE AND SQUARE IS THEN REVOLVED THRO' 180° AS SHEWN IN 2ND POSN.
SQUARE
PLAN 2ND POSN.
ELEVATION AND PLAN OF SQUARE IN 3RD POSITION TABLE AND SQUARE IS REVOLVED THRO' 90° FROM 1ST POSN. TO 3RD POSN. AFTER TESTING IN ABOVE VIEWS TABLE AND SQUARE IS REVOLVED THRO' 180° TO 4TH POSN. AND AGAIN TESTED.
PLAN 3RD POSN.
PLAN 4TH POSN.

FIG. 9

years. In spite of the work already carried out and the advances made, however, the air compressor is still looked upon as a weak spot in an otherwise reliable engine. This consideration, apart from elimination of mechanical complexity and loss of power involved in driving this detail, has led to increasing efforts being made to develop the Diesel engine using mechanical injection of fuel. The study of modern air compressors is, therefore, of interest to engineers from the point of view of appreciating the difficulties involved in their development and use, and the manner in which such difficulties have been or are being surmounted.

Compression Cycle.—Air may be compressed in accordance with either of two distinct laws or by the combination of the two; thus it may be accomplished isothermally where the temperature remains constant or adiabatically where the temperature rises, during compression. Less work is required in the case of isothermal compression and it is, therefore, an ideal to be aimed for. In practical cases, however, unless the speed is very slow, and this has the disadvantage that leakage losses (which depends on the time factor) are greater, true isothermal compression cannot be obtained. If water injection into the cylinder be adopted as in the case of torpedo air compressors, the rise of temperature can be minimised, but in Diesel engine work, where a supply of dry air is a necessity, the temperature rise can only be kept down by efficient jacketing of the cylinders. Actually, therefore, the compression in practice will be between the isothermal and the adiabatic, and some rise of temperature must



take place. Such a rise must be limited, otherwise trouble will be experienced with carbonisation of lubricating oil at the valves quite apart from the serious derangements that may arise should the flash point of the oil be exceeded. Practical considerations demand, therefore, that the ratio of compression in any cylinder should be limited and the high compressions actually required for the purposes under review must be carried out in stages, with cooling of the air between each stage. As it happens, this procedure, while necessary for the foregoing considerations, also lessens the amount of work required for the total compression since the mean curve of compression will thereby approach more closely the isothermal for the whole range. This can be appreciated by a study of the theoretical diagram for a 2-stage compressor given on page 55. The areas shown shaded indicate the increase of work (not to scale) due to departure from isothermal compression. It is not possible to lay down definite rules giving the maximum increase of pressure that should be carried out in any one stage, as it is dependent on the size and general design of the compressor itself and also on the conditions under which such compressor may work. As a rough guide only, however, the following figures may be taken :—

Single stage - - - - - -	100 lbs. per sq. inch.
Two stages - - - - - -	600 ,, ,,
Three stages - - - - - -	1,500 ,, ,,
Four stages - - - - - -	3,000 ,, ,,

It will be seen, therefore, for Diesel work where blast pressures in the neighbourhood of 1,000 lbs. are required, that three stages are desirable, if not absolutely necessary, whereas for H.P. air up to 2,500 lbs. required for torpedo work, four stages are necessary.

As illustrating the saving of work obtained by compressing in stages and by following isothermal compression more closely, the following figures representing the theoretical horse-power required to compress 1 cubic foot of free air per minute to 1,200 lbs. gauge pressure, according to the law $pv^n =$ constant, are illustrative :—

	$n = 1 \cdot 35$	$n = 1 \cdot 25$.
One stage - - - - -	·532	·454
Two stages - - - - -	·382	·355
Three stages - - - - -	·344	·330
Four stages - - - - -	·328	·317

Capacity.—The capacity of a compressor is usually expressed in cubic feet of free air per minute. This is not equal to the swept suction volume of the first stage of the compressor per minute, but something very much smaller, and the ratio between the two is termed the " volumetric efficiency."

In a marine Diesel engine the capacity of the compressor must be sufficient to keep all the fuel valves supplied with blast air plus a margin for recharging the manœuvring air receivers. It is usual to make the first stage cylinder stroke volume a percentage of the total stroke volume of the Diesel engine, this percentage varying considerably with the type of engine, *e.g.*, for a single acting type of compressor.

4-cycle engines.

Normal speed engines.—5 per cent. (large engines) to 7 per cent. (small engines).

High speed engines.—8 per cent. (large engines) to 11 per cent. (small engines).

For 2-cycle engines these figures require to be approximately doubled.

Under average working conditions it is desirable, in the interests of reducing the work expended on compression, that each stage of the compression should do an equal share of that work, and therefore pass the air through an equal compression ratio. In this case, the rise of temperature of the air in each stage is theoretically the same, and is the maximum possible for a given overall compression, assuming the air follows the same law in each case. For a machine serving a dual purpose as required for a Diesel engine compressor, these considerations cannot be assured under both conditions and, therefore, special attention needs to be given to this matter at the design stage if unfavourable conditions are to be avoided under either methods of working.

There is little doubt that a number of difficulties experienced in air compressors have been due to a want of appreciation of this point, and it is, therefore, proposed to consider it in further detail.

In nearly all cases a Diesel compressor is, or rather has been, designed with sufficient capacity to charge the starting air bottles as well as to provide the requisite quantity of blast air—and the dimensions of the stages have been considered from the point of view of this aggregate output. The period during which the compressor is used for the dual duty of charging starting bottles and supplying blast air, is a comparatively small fraction of the time it is working. So, for the greater part of its life, a compressor designed on this aggregate basis is running at reduced output, and the lesser capacity required under average running conditions is generally attained by throttling of the air in the first stage suction pipe. The result is the formation of a vacuum in the first stage cylinder and hence, seeing that the high delivery pressure is still required, the overall compression range is increased and attended by an increased rise in temperature in each of the later stages, and, as can be proved, more particularly in the final stage. Moreover, if the first stage is in communication with a crank case where forced lubrication is employed, the conditions for the passage of oil to the compressor are more favourable, and the difficulties arising from carbonisation of oil on the valves and the possibilities of explosion are aggravated. A better method of regulation which, although overcoming the former difficulties, entails a loss of efficiency, is to provide a free inlet for the first stage and to discharge the surplus air from the first stage intercooler, the compression ranges under all the various conditions of running being maintained sensibly the same.

Another point that may arise in connection with the first method of regulation is important. With certain arrangements of stages the loads on the driving mechanism may be larger under reduced than under full-power conditions, and considering that the reduced output conditions are operative during the greater period of service of the compressor, the procedure leads to a notable increase in wear and tear during the lifetime of the engine. Such a condition arises in a typical vertical 3-stage compressor on one line where the second stage is formed by an annulus below the first stage piston. The loads due to first and third stage compression will be always downward whilst that of the second stage is upward. It can be demonstrated that under throttling conditions, due to a falling-off of the upward force, the net load on the crank-pin, etc., actuating the plungers is increased, thus entailing higher bearing pressures. As in the general case the load is also always downward it is very important that careful attention should be given to the bearing surfaces and lubricating arrangements if derangements or excessive wear at these positions are to be guarded against. The arrangement of stages referred to is a very common one, as it has the advantage of placing the second stage in communication with the crank case and the higher air pressure at this position serves to prevent access of lubricating oil to the compressor.

A further method of regulation has been proposed to overcome some of the foregoing difficulties, viz., the fitting of an additional cylinder which is idle under blast conditions but forms the first stage of the compression under charging conditions, *i.e.*, the machine can be made to work as a 3- or 4-stage compressor at will. It may not always be possible to guarantee minimum work conditions with either arrangement, but it offers a solution likely to overcome the practical difficulties referred to with the simpler method.

It is not necessary to consider in detail the arrangements of stages in different compressors, as some of the principal points to be borne in mind can be appreciated from what has been discussed. With 4-stage work, however, it is generally arranged to fit two stages on each of two lines as such a combination, besides decreasing the complexity obtaining on one line, is susceptible of being balanced, provided the two cranks are arranged at 180°. Variations from some of the arrangements indicated are also seen in the well-known Reavell compressors where the stages are grouped at equal angles round a common crank-pin.

Valves.—The valves used in air-compressors are in all cases automatic in action and, apart from their design, care must be given in arranging them so that the passages to and through them increase by as little as possible the cylinder clearance, the value of which exercises an important influence on the volumetric efficiency. The valves must be large enough to limit the suction air-speed through them to about 140 ft. per second as a maximum. To keep within this limit and to secure a practical design of valve, hey may have to be of the multiple type in the first stage. The most efficient type of valves for air compressors is of the plate type, the plate being provided with a number of circular slots, making it, in effect, a number of light rings joined at various points to provide the necessary continuity and stiffness. The faces of the rings are ground and they seat on very narrow faces on the housing, and as the area through the valve is equal to the total circumference of the slots multiplied by the lift of the valve it follows that large areas of flow are obtained for very small lifts. This type of valve, then, is preferable for compressor work, as it embodies many of the features that are so necessary for efficiency. The material and thickness must, however, be such that the valves do not crack or break on the one hand, and on the other, that they will not deform so as to cause leakage of pressure air during operation, and it is difficult to compromise these features satisfactorily. They are made preferably of an alloy steel which, apart from valuable strength properties, has also a good resistance to corrosive effects. The cage above the plate valve is provided with a number of small springs, comparatively lightly loaded, while a number of small pegs or guide pins keep the plate located on the faces. Nickel plating of the springs is recommended to prevent corrosion. In the H.P. stages, where the areas required are small and plate valves cannot be accommodated always, thimble and poppet valves are common.

Intercooling.—The necessity for intercooling between the stages has been indicated and there are various types of cooler in use. One type consists of a coiled tube immersed in a cast-iron box, water being circulated over the coil. With such arrangements the coils need to be clipped in places by strips of lead to prevent any vibration in the coil which would tend to distress the material and start cracks. Another type, and this is rapidly finding extended use, consists of straight tubes expanded into tube-plates, it being generally preferred with this type from structural considerations, to arrange for the air to flow through the tubes and the water in a suitably baffled circuit around them. Where the air travels through the tubes there is a possibility in the higher stages that, should any of the tubes fail, the high-pressure air would leak into the body and this, not being designed for high pressures, would fail with possibly serious effects. Safety discs are therefore fitted to the bodies. The necessary thickness of disc is usually determined by arranging to burst one or more during the water-pressure tests. As moisture is generally separated from the air in its passage through the cooler, provision is made for collecting it in a small separator at the lowest point, and which, with a certain amount of deposited grease, can be periodically blown off.

All cylinders and covers require to be well jacketed, and it is preferable to arrange for separate liners, usually of close-grained cast-iron, being fitted to all stages. Such construction is an advantage in the event of wear as regards facilitating renewal; also the liners can be made thinner than in the case when the working barrel forms an integral part of the cylinder casting, which is of advantage in assisting towards cooling. The whole of the valves should preferably be cooled but this can only be done by increased complexity and rendering the valves difficult of access. Valves, in any case, require frequent examination, if only for cleaning, although the necessity may be less if they are water-cooled.

Clearance.—The necessity for very small cylinder clearances has been mentioned. At the end of the compression stroke of the first stage, say, the clearance volume will be filled with air at 100 lbs. pressure. No fresh charge can be inducted till the piston has moved back a sufficient distance to permit this pressure falling to slightly below atmospheric. The remainder of the stroke only is effective, and it can, therefore, be easily appreciated that the volumetric efficiency of the compressor is markedly dependent upon the clearances allowed. Taking the minimum bumping clearance practicable and allowing for the shortest passages to the valves a good design should keep the clearance volume below 4 per cent. of the stroke volume whilst in favourable cases 2 per cent. may be possible.

The air-tightness of piston rings has an obvious bearing on the volumetric efficiency obtained and consequently on the horse-power required per cubic foot of air delivered.

Leakage.—Leakage past the piston rings being a function of time, tightness of piston rings might be stated to be of less relative importance with high piston speeds than with slower speeds. In multi-stage machines piston ring leakage, which tends to increase as the pressures become higher in the later stages, has the effect of increasing the pressures at the lower stages. The experience obtained by one well-known firm of air-compressor makers, indicates that better results are obtained if the piston rings, while accurately machined to the cylinder diameter, can rely for their spring pressure upon a spring ring behind the packing ring, than if spring-over rings are fitted. This, however, is by no means general practice, and spring-over rings are common in all stages of machines supplied by other reputable makers and give general satisfaction. In small machines it is not unusual to dispense with rings in the H.P. stage and to fit a solid plunger, made a near fit in the bore, a self-aligning arrangement being usually provided to permit of its adjusting itself in the event of possible relative displacement.

Lubrication.—Lubrication of compressors is usually arranged for by a mechanical lubricator passing oil to the cylinder at one or two positions near mid-stroke, circumferential channels of a slight wavy form being sometimes cut in the barrels to secure distribution of the oil. Special mineral oil with a high ignition point should be used, but it is favoured practice with some makers to use a compound oil, *i.e.*, a small percentage of an animal oil is blended with the special mineral. It is claimed that the carbonising effects are reduced with such compounding, the effect of the added oil being to keep all surfaces cleaner, and although beneficial effects have been claimed by a number of users, there is by no means unanimity on this matter. The varied conditions under which compressors work are probably not without influence on this question.