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# PRESIDENTIAL ADDRESS

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May I say, to start with, how very much I prize the honour which you have done me in asking me to become President of this Institute, a body which is doing such a valuable and useful work for all its members. It is a very nice gesture on your part to invite a shipbuilder, from time to time, to fill this position—a compliment which is much appreciated.

Last year Lord Rotherwick made a very strong point in his address to you of the paramount importance of reliability in marine machinery. I would like to stress this subject again, as it is of such vital importance. Motor cars, railway locomotives and power stations may have temporary breakdowns without either such serious results or so much publicity as those which attend the breakdown of a ship. The financial effects of a breakdown in a ship are often extreme, not only in repairs, but in loss of earnings, in chartering other tonnage and in various other ways. It follows, therefore, that progress in marine engineering is attained by many short cautious steps rather than by a few long bold ones.

There is another consideration which affects the future progress of marine machinery and that is the fact that considerable progress has been made in the past, so that each further step becomes more and more difficult. The advances which were made in the early days of steam machinery meant that the improved engine had only to be compared with its very inefficient predecessors. But now that temperatures and pressures have risen and any further advances in efficiency are likely to require still higher temperatures and pressures, there are obvious difficulties in reliability and manufacture.

The margin left for improvement is manifestly becoming smaller and the rate, at which the cost of more efficiency is achieved, is rising. Undoubtedly, further efficiency in fuel consumption can be achieved, but sometimes the cost of doing so is such that the gain in technical efficiency means a loss economically. A point is sometimes reached when the depreciation, insurance, interest, upkeep and other charges on the extra first cost more than outweigh the saving in the fuel bill and any savings due to smaller bunker space and weight. Progress must therefore be dependent to a certain extent on keeping first cost within bounds by simplification of design and as sparing a use as possible of the more expensive materials.

I have referred really to the main propulsion engine but we must not forget that there are many other factors of efficiency or inefficiency. Most of us can, I am sure, recall cases where the benefits of good performances by main engines were thrown away by losses in the auxiliaries, by a bad propeller or by a hull that was hard to drive. But all these have been and are being improved. Much research has been done of late years and much is still going on.

The problem for fighting ships is rather different, for fighting qualities, such as speed and radius of action, largely outweigh the pounds, shillings and pence aspect. It is likely therefore that in many ways naval machinery may force the pace ahead of merchant machinery in the use of high temperatures and pressures.

But in merchant ship design there is one point in which I do not think that progress has been made, and that is in the design of funnels. I look back with regret to the tall, thin, graceful funnels of fifty years ago. They certainly gave less trouble with smuts on the boat deck and there was no need for some of the curious varieties of form of funnel top which one sees nowadays. I know that the tall funnels are out of fashion just now, but let us see what the arguments are for the thin tall funnel as against the short wide one.

Without paying any attention to the æsthetic side of the question or to current fashions, the short wide funnel has the advantage of being able to house all sorts of equipment, such as silencers, water tanks, overflow pipes and even in some cases the Captain himself. On the other hand, it is heavier, more expensive and more difficult to drive through the air, and a good deal of trouble has been experienced from the flue gases descending on the boat decks, making them dirty and sometimes destroying lifeboat covers, etc., and even silk stockings.

Experiments on the flow of funnel gases show quite clearly that a tall thin funnel overcomes this difficulty. Moreover, it is more easily driven through the air and therefore more efficient from that point of view. The blowing of tubes becomes a much less anxious operation for the officers in a ship with the taller funnel.

It seems to me that, apart from fashions and looks, the balance of advantage is against the present funnels. Perhaps when a new generation arises, it will look for change for the sake of change and discover— all at once—that the tall thin funnel is much to be preferred.

We are apt sometimes to be a little superior when referring to women's fashions, but it seems to me that no woman was ever a more helpless slave to fashion than the shipowners and shipbuilders of today. But from the shipbuilder's point of view, fashion is, of course, a very good thing as without changes of fashion, fewer ships would be built.

Here again, the problem for the fighting ship is different from that of the merchant ship. A large funnel is obviously a better target and more easily spotted than a small one and I should not be surprised if, on fighting ships, funnels, as we know them, disappeared altogether and some form of light pipe took their place.

As well as streamlining funnels, there is a fashion at present to streamline the houses and other erections on the ship. A modified amount of rounding corners may be all very well. For one thing, that part of the resistance, to the forward motion of a ship, which is due to air resistance, is small compared with the resistance of the water and that part of the air resistance which can be saved by streamlining is very much smaller still—in fact it is comparatively speaking nil. It must be remembered, too, that the speed of a ship through still air is much less than the speed of a land vehicle, while the ship is more likely to meet the full force of the wind. And the chances of a side wind are twice as great as those of a head wind. With a side wind the effects of streamlining are considerably less. Perhaps the story of what happened on the railway trains may be of interest. After the streamlined locomotives had appeared, someone suggested that the eddies of air at the gaps between the carriages could be overcome by fitting some sort of plates to cover these gaps. This was done, but the speed of the train suffered a decrease instead of an increase because side wind increased the sideways pressure of the train and therefore the side friction on the rails. The cover plates were removed and at a later date so was the streamlining on the locomotives, although for a different reason.

A streamlined deckhouse is obviously more expensive to build and much less economical of the space it contains for accommodation.

But to come back to engines again, it will be very interesting to see what the trend will be in the future. This trend will largely depend on the costs of the various fuels available—not only the costs of buying them but of handling them too. The virtual disappearance of coal as a fuel for the larger ships would have surprised the engineers of fifty years ago, could they have seen the world today. The Diesel, or internal combustion engine, is today a strong competitor with the steam engine, whether reciprocating or turbine, although it is limited to what are today considered moderate powers. But in less than fifty years' time, all Diesels may be burning the cheaper boiler oil and doubling the power by gearing twin engines to one propeller shaft. And to advance still further, will the gas turbine or the atomic energy machine have ousted the Diesel and steam turbine? The gas turbine has still some way to go and one of its main advantages—that of reduced size—is still neutralized by the archaic methods of measuring tonnage, which puts a virtual prohibition on making engine rooms less than 13 per cent of the ship's gross tonnage. But if the tonnage laws were altered and if the gas turbine overcomes all the difficulties of burning heavy oil and of using higher temperatures still, then we may see the gas turbine in general use.

The atomic energy ship as a commercial proposition is still very difficult to assess. No one knows what the fuel may ultimately cost, how long a ship will be able to go without bunkering and what the difficulties of doing it may be. But if these difficulties are overcome and the cost becomes low enough, it is easy to see that this form of propulsion may have distinct advantages, with the fuel for a long voyage brought on board, so to speak, in a suit case.

In all forms of machinery the development of welding is likely to extend the tendency, which has been evident for some years, for substituting fabrications for castings. Once a suitable design of fabrication has been evolved, it is usually found that the fabricated structure is cheaper and lighter than the casting. For the larger heavier castings, this is often so, if not always for some of the smaller ones.

Parallel with this tendency in machinery we see today an increasing tendency towards welding in the hulls of ships. One reason for this is the likelihood of a distinct dearth of riveters in the future. Very very few boys are now becoming apprentice riveters and the average age of the existing squads is gradually getting higher and higher. On the other hand, the supply of welders is increasing. It is easy to see the boys' point of view, for, apart from the nature of the job and the physical effort needed for the work, so much has been written and said about welding that they feel that riveting is a dying trade. I see no signs at present of this tendency being counteracted, so that it looks as if it will continue, for this reason, if for no other. There are, of course, other reasons both for and against welding. One gets a distinctly lighter hull in a welded ship and the smoothness of the bottom gives a more easily driven hull. The structure is also cleaner with fewer corners, where moisture may lodge and start corrosion, while the decks and tank top are flatter, making the work on top of them easier.

As to whether welding really cheapens a hull it is perhaps too soon to give a definite answer. Undoubtedly it has cheapened quite a number of fittings, especially smithwork. But the process of making large welded sections of ship and then sticking them together on the berth is not so easy as it looks and often runs away with a lot of money in fairing and fitting. We still have a good deal to learn about the right methods to employ. But one lesson is clear—that welded work must be much more accurate than riveted work. If it is not accurate, up go the costs. These lessons are being learned and gradually more satisfactory techniques of dealing with welded sections are being evolved. I, for one, feel that ultimately the cost of the all-welded, or almost all-welded, ship will be less than that of the riveted ship but, at that stage, it will probably be difficult to get an all-riveted ship at all.

Some doubts have been cast regarding the repairing of welded ships, but I do not see why repairers should not be able to adapt their methods to welded ships perfectly satisfactorily.

One often sees statements that the cost of ships has gone up by so many per cent compared with pre-war days or with some other period and examples are given of building what they call a "similar" vessel today. Now no owner today ever builds a ship similar to his pre-war ship. For one thing, various regulations have changed and he is forced to follow them. In almost every case this adds considerably to the cost, one very substantial item being the new standards for officers' and crew accommodation which, on the average, are very much better and roomier than the pre-war standard and require a good deal more deck houses or other space to accommodate them.

Almost inevitably also various improvements are made in many directions—better cargo gear, better stores, better refrigerated chambers and a host of such items. Finally, the speed is almost always increased and a more expensive type of main engine fitted, usually with oil fuel and often with a vastly greater electric installation.

Comparisons of cost between pre-war and post-war ships are always entirely misleading, and the only way of making a true comparison is to get shipyard and machinery estimators to make estimates on the two specifications.

Shipowners can still help themselves, to a certain extent, by going through their own specifications with a critical eye.

Finally, may I say a few words about the Research which is going on at present. As you know, there are two research organizations, the British Shipbuilding Research Association and the turbine research organization known as Pametrada. The former deals with all aspects of ships and machinery except turbines, both steam and gas.

Pametrada has a large research and testing station on the Tyne. Here steam turbine sets up to 60,000 s.h.p. can be tested against an electric brake and accurate measurements are taken. Pametrada also has a design section for steam turbines, which supplies designs to members, and continuous research is going on to provide data for the design section.

A gas turbine of some 3,500 s.h.p. has also been built and has been run, therefore on both steam and gas turbines, very active progress in research is now being made.

B.S.R.A. works in rather a different way. The field here is so wide and the items so varied that the actual work, in most cases, is done in ships at sea and in laboratories, universities and works all over the country. Apart from a large testing machine situated at a steel works, and a small laboratory, B.S.R.A. has no research establishments of its own. The work is controlled from the head office in London which, in addition to the management and technical staff, houses the library department. This library has now accumulated a very considerable amount of data and should be able to give an enquirer information regarding all the publications on any particular subject or aspect connected with ships or machinery. This should prove of great value to the technical side of industry.

But the most useful laboratories are the ships themselves and research teams have attended many trial trips and have completed many voyages collecting data of all sorts and on all sorts of subjects.

You may have seen recently in the Press, references to the trials which are being carried out with the *Lucy Ashton* on the Clyde. She is an old paddle steamer, found in the shipbreakers' hands with the upperworks and paddles all stripped. In order to find the accurate propulsive thrust without disturbing the water with paddles, propeller or tow rope, aeroplane jet engines have been suspended from a framework on board and very accurate measurements of the thrust can be made. These engines are extremely noisy and are not an efficient medium for propelling a ship in service, but for this particular purpose they are ideal. It is hoped that very useful data will be obtained on the resistance of a naked hull and on the effects of skin friction. Experiments of this sort have not been made since Froude's famous *Greyhound* experiments last century.

A very large proportion of the total work going on is on propelling machinery, principally on Diesel engines and on boilers—but no one has yet found a suitable substitute for the wrought iron boiler tube!

# Some Interesting Points on Lubrication*

H. NICOL (Graduate)

The object of this essay is to outline briefly, for the benefit of those junior marine operating engineers who do not fully appreciate the necessity for giving a reasonable amount of time and thought to the intricacies of efficient lubrication, the fundamental principles involved in the lubrication of the most important parts of a Diesel engine.

In modern Diesel installations with completely enclosed crankcases and forced lubrication, if the bearing temperatures remain stable, there would seem, at first sight to the inexperienced, to be no doubt whatever that the bearings are behaving as they should. This, of course, may not always be the case, as excessive wear could be occurring and the heat generated taken away by an increased flow of the lubricant—thus maintaining the low temperature.

The reduction of wear in the main bearings, piston rings, cylinder liners and all moving parts is of prime importance to the efficient performance and service life of an engine. This can best be achieved by using a lubricating oil of good quality, correct viscosity and oiliness, maintained in clean condition by effective purification.

The oil used in Diesel engine forced lubrication systems, is generally pure mineral oil. The final test of an oil, however, is its behaviour under service conditions.

The two most important properties of a lubricating oil, so far as the reduction of friction and the supporting of heavy loads are concerned, are viscosity and oiliness.

The viscosity is a measure of the resistance encountered when one layer of lubricant slides over an adjacent layer. For commercial purposes the viscosities of liquids are measured by observing the length of time taken in seconds for a measured volume of oil to flow through an orifice of given dimensions under specified standard conditions. A typical instrument used for this purpose is the Redwood viscometer. It should be noted that the viscosity of an oil diminishes rapidly with increase of temperature, but is only slightly affected by pressure.

The oiliness of a lubricating oil is a property which is slightly more difficult to explain. Two oils could have identical viscosities but could have different degrees of oiliness, in so much that the friction force of one will be less than the friction force of the other. The oil possessing the least friction force is understood to have the greater oiliness. It will be appreciated, therefore, that viscosity and oiliness are entirely different properties, and which of these properties exercises the controlling influence on the friction between two rubbing surfaces depends upon the thickness of the layer of lubricant.

For engine cylinder lubrication mineral oils have been used extensively in the past, but they were found unsuitable for use under boundary lubrication conditions, where, as already pointed out, oiliness is the all important factor in determining frictionless movement. However, it is still quite common practice for mineral oils to be used in trunk piston engine cylinders, where the piston enters the crankcase every revolution and carries a considerable amount of crankcase oil into the cylinder. In engines where the crankcase and cylinders are completely isolated, compound oils are generally used, as it has been found that by adding a small proportion of vegetable oil, which possesses a high degree of oiliness, to mineral oil, which is relatively deficient in this property, better performance under service conditions has resulted.

Engineers, during the early part of their training, are called upon to make various experiments in connexion with friction, one of which is to ascertain the forces necessary to overcome friction between surfaces. For example, when two similar or dissimilar metals come into contact, and forces are applied to move one or both, so that one moves oppositely to, or in the same direction, with a velocity relative to the other, resistance to such movement will be realized. The resistance encountered varies with different materials, but all materials offer resistance to such movement, being due mainly to the load on, and the nature of the surfaces in contact. The less the load and smoother the surfaces the less will be the frictional resistance to movement.

Should power be supplied to overcome this frictional resistance it will be converted into heat, the surfaces in time becoming exceedingly hot, and if suitable cooling means are not provided, seizure will take place. If means are provided to carry off the heat generated, the metals will be ground to powder in a short time. The cooling medium, of course, must not be permitted to make contact with the rubbing surfaces. It will be realized then that the various parts of machinery which come in contact with, and move in relation to, other parts, must be separated by some suitable medium which offers very little resistance.

All gases and most liquids offer very much less frictional resistance to relative movement than solids, and oils are the most suitable for the purpose. In practice, a bearing supports a moving shaft by means of a thin film of oil. The fact that a very thin film of oil will keep surfaces apart, even when loaded to extremely high pressures and speeds, has had the attention of engineers and scientists for years and many experiments have been made, and formulæ evolved, to obtain a greater degree of perfection in both design and maintenance of moving parts for a wide range of purposes.

Beauchamp Tower was the first to make a study of film lubrication, and with the aid of his experiments, which he carried out for the Institution of Mechanical Engineers and which are fully recorded in their Proceedings of 1885, he disclosed that the pressure around the circumference of a bearing varied; the maximum pressure being taken in the vicinity of the centre of the bearing and tapering off to zero at either side.

The apparatus which Tower used is illustrated in Fig. 1

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* This essay won the combined Jacobs, Murdoch and Robertson Award for 1949.

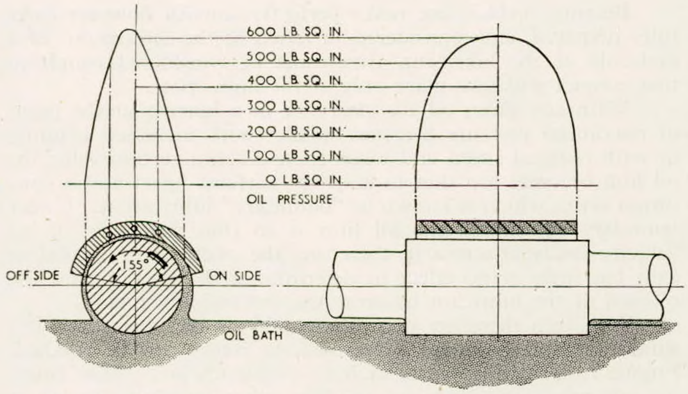

FIG. 1—*The original experiment of Beauchamp Tower*

and consists of a half brass resting on top of a revolving shaft, the shaft being partly immersed in an oil bath. The brass was 4 inch diameter by 6 inch long and subtended an arc of 155 deg. at the centre of the shaft.

Due to the motion of the shaft in the oil bath, the oil was carried up under the brass and when the brass was loaded considerable pressure was created in the oil film. The brass, as seen from the diagram, did not remain symmetrical about the shaft, instead, it moved slightly to the "on" side, making the oil film a wedge shape round the shaft, the thinnest part of the film being on the "off" side. Pressure tapping points were arranged around and along the brass and the pressures at these points were noted and plotted to give the curves shown, which shows a rapid increase of pressure from zero at the edge on the "on" side, to a maximum near the centre slightly to the "off" side, and reducing to zero at the outlet at the "off" side. The area under the curve represents the magnitude of the load carried by the bearing. Experiments made with shaft running partially and completely immersed showed identical results.

These early experiments by Tower, led Osborne Reynolds to formulate a mathematical theory of lubrication, the paper on which he read before the Royal Society in the year 1886. Reynolds established the relationship between the load sustained, the viscosity of the oil, the relative speed of the moving surfaces and the thickness of the oil film. Others after Reynolds, such as Professor Goodman, Sir Thomas Stanton and Professor Swift, experimented further, with a view to reducing the less rational assumptions which had hitheto been made.

With film lubrication the bearing surfaces are completely separated by a layer of lubricant so that frictional resistance arises from the relative movement of the layers of oil and not from contact between the actual surfaces. This is the ideal form of lubrication, but unfortunately the necessary conditions, to produce and maintain an oil film between the surfaces, can only be satisfied in certain types of bearings. Lubrication in a journal bearing is essentially a mechanical process. The journal and bearing are arranged so that the diameter of the journal is slightly smaller than the diameter of the bearing. The journal drags the oil into the clearance and forms a wedge shaped film which results in the hydrodynamic lifting of the journal. The journal is then sustained in a dynamic floating position under which only fluid friction is present (Fig. 2).

The greater the clearance, the less will be the loading capacity of the bearing as the oil layer will be squeezed through more readily. Therefore the smaller the clearance, all other factors taken into consideration, the greater will be the loading capacity. In addition to ensuring a definite clearance the bearing surfaces should be machined true and cylindrical and it is necessary to ensure that the axes of the shaft and bearing are parallel.

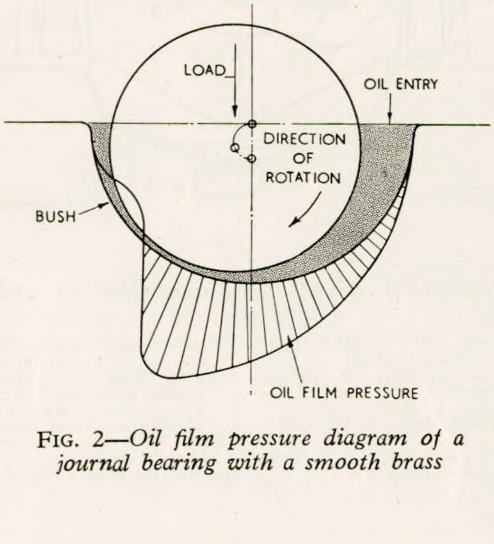

FIG. 2—*Oil film pressure diagram of a journal bearing with a smooth brass*

The oil supply should be introduced on the unloaded part because the findings of Tower showed that the pressure of the oil wedge in the clearance space under active load is incomparably higher than the pressure at which the oil is supplied to the bearing. The usual method for distributing the lubricant is to arrange recesses with wedge-shaped passages to the bearing surface. The recesses, of course, must not be allowed to extend to the ends of the bearing (see Fig. 3).

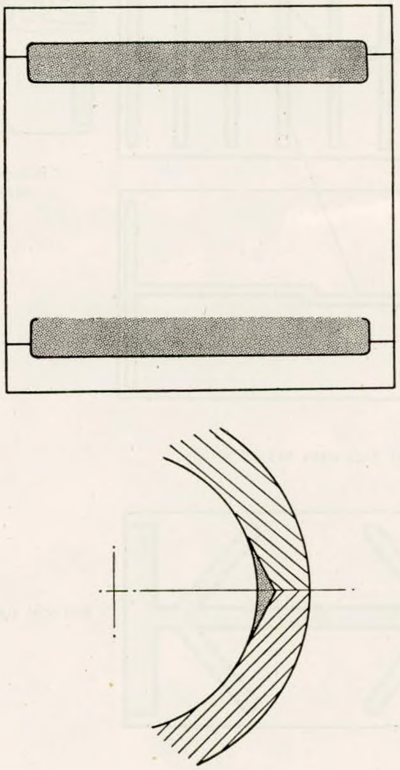

FIG. 3—*Design employing recess with wedge-shaped passage for distributing the lubricating oil over bearing surface*

Oil grooves wrongly arranged on the bearing surface can have detrimental results through failing to produce the required oil film, thereby reducing the loading capacity and reliability of the bearing. This will be appreciated by the comparison made between the diagram of the oil film pressure for an ungrooved half-brass and that of a half-brass in which is arranged three longitudinal oil grooves extending the whole length of the bearing. Fig. 4 shows the reduction of the oil film pressure diagram, which is some 70 per cent less than the loading capacity of the bearing, indicated by the dotted line.

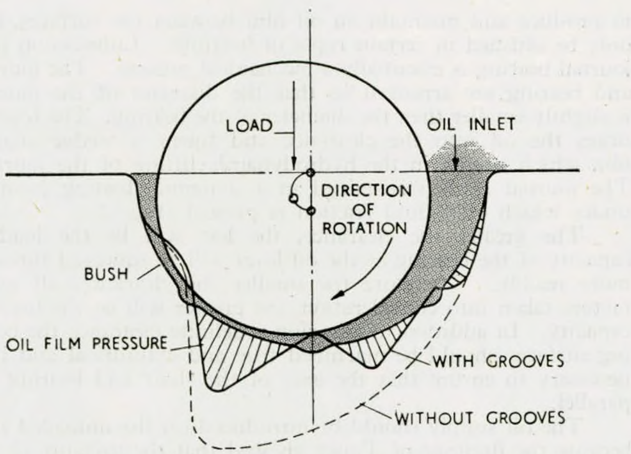

FIG. 4—*Oil film pressure diagram for a bearing with three longitudinal oil grooves extending to the end of the brass*

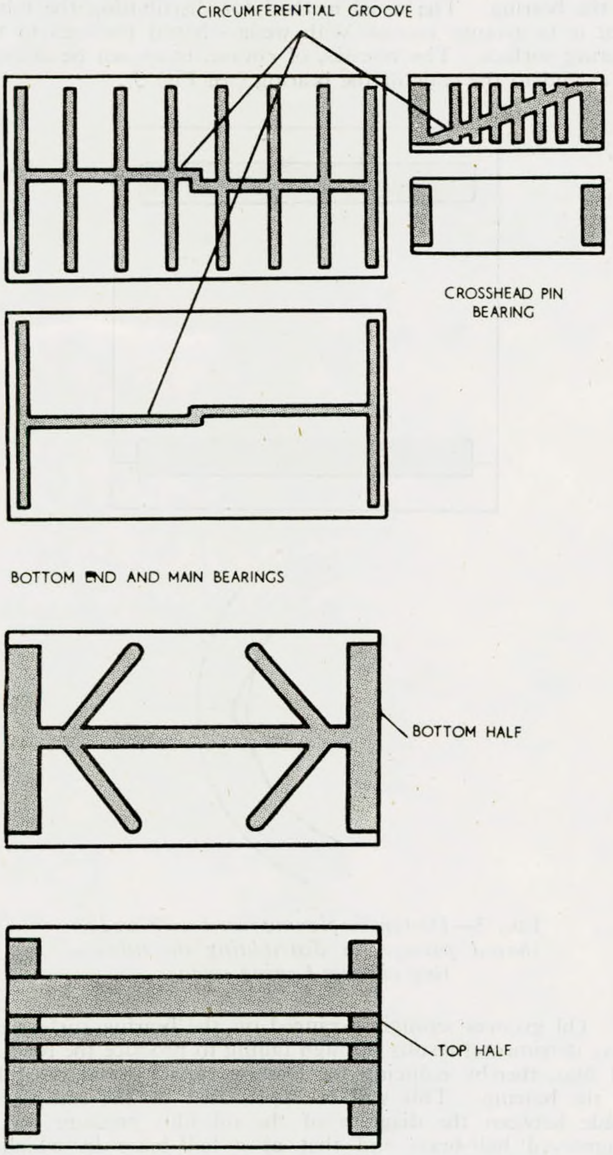

FIG. 5—*Developed bearing surfaces showing effective designs for main, crankpin and crosshead pin bearings*

Bearing surfaces are never perfectly smooth however carefully prepared, and, considered in terms of the dimensions of a molecule of the lubricant, they must be considered rough so that contact will take place only at the high spots.

With any given oil the clearance in a bearing at the point of maximum pressure becomes smaller with increased loading, or with reduced speed and when these reach a certain value the oil film becomes too thin to keep the surfaces apart and a condition arises which is known as "boundary" lubrication. Under boundary conditions the oil film is so thin that there is no velocity gradient across it, therefore, the viscosity of the lubricant has little or no effect in determining the friction and the oiliness of the lubricant becomes the determining factor.

Although there are two different kinds of lubrication, i.e., fluid film and boundary, intermediate stages can be reached. Engine recipricating parts, such as crossheads and piston rings, do not readily produce an oil film when moving slowly, or when heavily loaded. Even when running normally they do not produce a fluid film as readily, or to the same extent, as a revolving shaft.

In Diesel engines the principal bearings operate under fluid film conditions, but with decreasing engine revolutions, the hydrodynamic lifting effect on the journals and crankpins is also decreased. The pumping action of the journals and pins becomes less and less as the engine speed is reduced, and the fluid film gets thinner and thinner, until just before stopping lubrication no longer depends on the viscosity of the lubricant, but upon its oiliness; the friction between the sur-

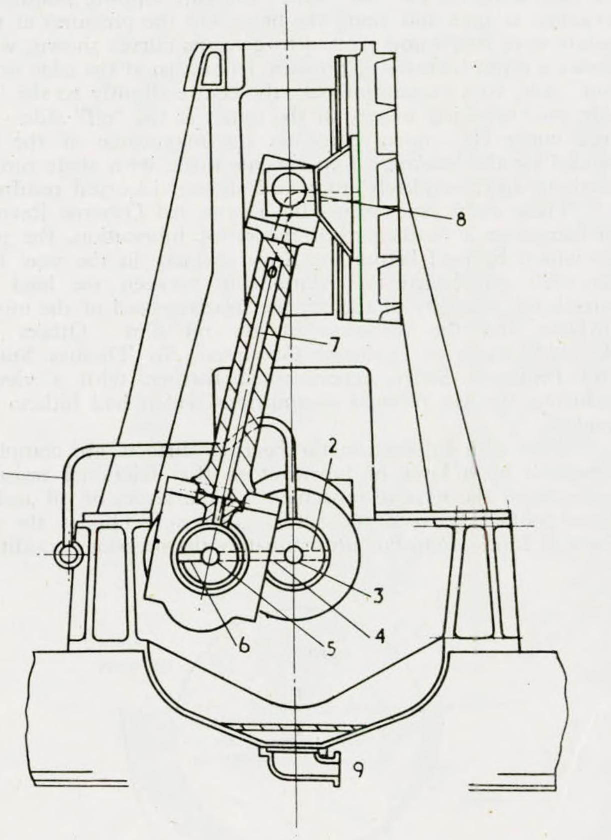

FIG. 6—*System of forced lubrication (Harland and Wolff engine)*

1.—Lubricating oil supply from pumps to main bearings.
2.—Radial oil in shaft for oil to enter central hole of shaft.
3.—Central hole in shaft.
4.—Hole through crankweb to crankpin.
6.—Radial hole in crankpin to bottom end and connecting rod.
7.—Hole through centre of connecting rod up to crosshead pin.
8.—Hole from crosshead pin to guides, from which the oil after use drains down to well in crankcase. It is then pumped out, filtered, and cooled for further service.
9.—Drain to lubricating oil tank.

faces is then that of boundary lubrication. Naturally, it follows that the opposite sequence will occur when starting.

Forced lubrication has been adopted in Diesel engines to ensure efficient circulation of the lubricating oil. This is essential for two reasons, firstly, to ensure ample oil for lubrication, and secondly, to provide a generous supply to carry off the heat generated. In early days the importance of this latter requirement was not sufficiently appreciated and before satisfactory engine performance was obtained experiments had to demonstrate its importance. Although it would appear that each manufacturer has his own idea regarding lubrication details, it will be found that the basic principles apply.

Effective designs of main, crankpin and crosshead pin bearings are shown in Fig. 5. It will be seen from (a) that the circumferential groove is stepped, so as to prevent the formation of ridges on journals and pins. For a similar reason the longitudinal grooves are spaced so that the angle between them is less than the swing of the connecting rod. It should be particularly noted that the arrangement of grooves and holes enable the lubricating oil to circulate quickly with small temperature rise. The system most widely adopted is one in which oil is supplied under pressure to all bearings (see Fig. 6). In this system a lubricating oil pump, main engine driven or independently driven, draws oil from the clean oil section of a lubricating oil drain tank and discharges it through a filter and cooler to a main supply pipe, running along the side of the engine, and thence through branches led to each main bearing. From the main bearings the oil passes through holes in the crankshaft journals, webs and pins to the crankpin bearings thence through longitudinal holes in the connecting rods to the crosshead pin bearings and in some cases to the crosshead guides and shoes, from which it drains to the engine drain tank *en route* the engine sump.

In Fig. 7 the oil is supplied to the main bearing through the supply pipe, arranged at top of keep, and enters pockets, arranged in keep and housing, under pressure. Wedge-shaped grooves are provided in the top and bottom halves of the bearing and are supplied with oil under pressure, through the connecting holes, from the pockets. Large wedge-shaped recesses are cut in the whitemetal at the sides of the bearing. A deep circumferential groove is arranged at either side of the bearing and communicates with each of the oil pressure pockets by means of comparatively large holes. The radial holes in the journal are so placed that at least one hole is passing oil under pressure to the connecting rod bearings during a revolution.

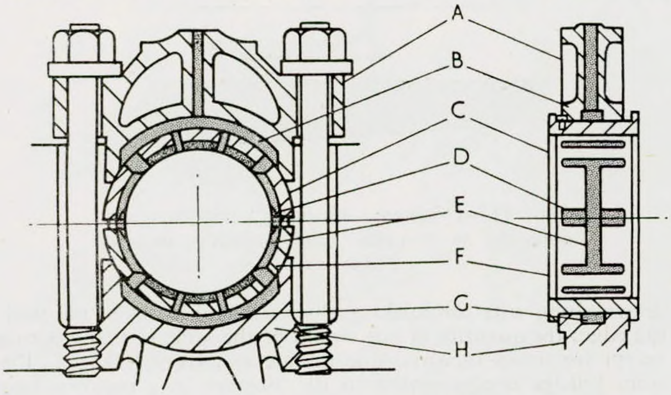

FIG. 7—*Main bearing (Burmeister and Wain patented construction)*

A—Bearing keep.
B—Oil pocket in bearing keep.
C—Top half of bearing bush.
D—Wedge-shaped oil recess.
E—Circumferential oil groove.
F—Bottom half of bearing bush.
G—Oil pocket in bearing housing.
H—Bearing housing arranged in cross-member of engine bedplate.

The oil passes from the journal through the holes in web and pin to the crankpin bearing. Holes are arranged in the crankpin bearing, in a similar manner to those of the main bearing (see Fig. 8) through which the oil is then forced up the hole, the connecting rod to crosshead pin bearing and crosshead shoe, as shown in Fig. 6.

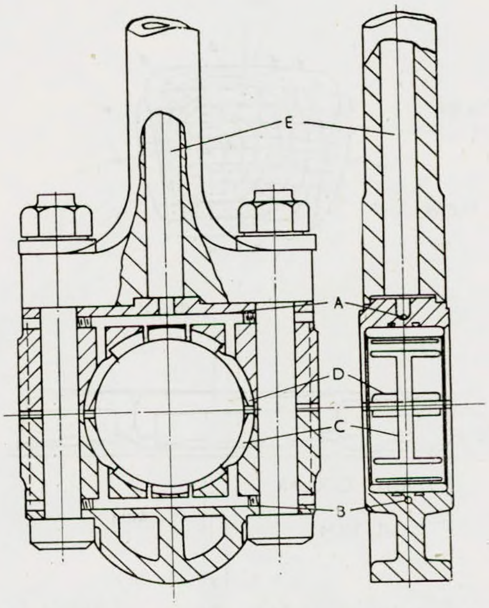

FIG. 8—*Crankpin brasses (Burmeister and Wain patented construction)*

A—Oil pocket in top half of bearing.
B—Oil pocket in bottom half of bearing.
C—Circumferential groove.
D—Wedge-shaped recess.
E—Hole, drilled concentrically in connecting rod, through which oil is supplied to crosshead pins and shoe from crankpin bearing.

To meet the higher ship speeds and powers, thrust systems require careful designing in order to withstand the enormous axial loads imposed by the propeller.

This problem was more acutely felt by the earlier engineers, who, to meet increasing speeds and powers in their day did the obvious thing, that is, increased the number of thrust collars on the shaft. By so doing they increased the bearing area and reduced the bearing pressure to a suitable value to take the increased loading. It was not considered desirable to design such bearings for pressures above 50lb. per sq. in., and current practice at that time aimed at considerably less than this figure. The troubles experienced with these multi-collar arrangements were numerous indeed, and suffice it to point out that the variation in linear expansion became more accentuated with the number of collars employed—and adjustments made when the parts were cold were nothing like those realized when the shaft and the block became heated—and cases arose where there were only one or two collars at one end taking the whole load with dire results.

A. G. M. Michell made a study of Reynolds' theory and succeeded in applying the principle of film lubrication to thrust bearings. He experimented and found that he could produce the required conditions for film lubrication by arranging separate pads around a fixed collar, in such a way that each pad could pivot about a point so that the bearing surfaces of the pads took up positions relative to a collar arranged integral with a revolving shaft. Thus each pad permitted a wedge-shaped film of oil to form between it and the collar (see Fig. 9). Michell took out a provisional patent in 1905 for his discovery entitled "Improvements in Thrust and Like Bearings" and the salient features of his specification are:—

"According to this invention only one of the bearing parts has the form of a continuous collar, ring or disk. This may be either the fixed or the moving part. The other bearing part, in place of being also a continuous ring or disk, consists of two or more separate plates or blocks, each forming substantially a sector of such ring or disk.

"Each block is pivoted at a point somewhat behind its centre of figure, the portion of total bearing pressure which the block carries being transmitted to it by such pivot.

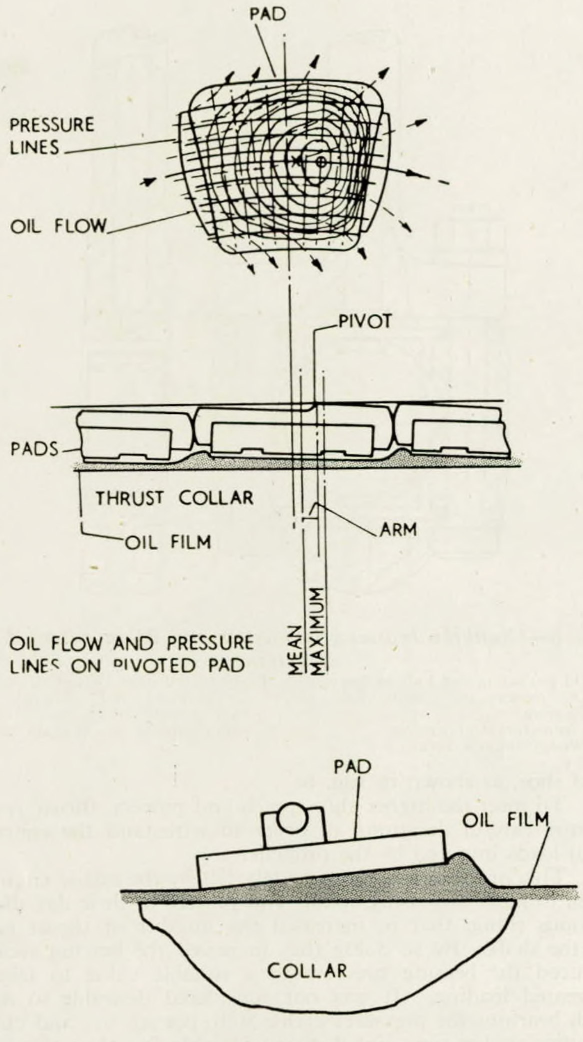

FIG. 9—*Michell thrust pad*

"The object of this arrangement is that the film of oil between each block and the surface on which it bears may be more compressed or restricted at the rear end than at the front or leading end of the block, a condition which favours the entry of oil between the surfaces at the leading end".

The pivoted sectors, now widely known as thrust pads, were correctly proportioned by Michell, and in spite of the numerous experiments which have been made experience has proved that variation from the original shape has not in any way enhanced the efficiency of the block, hence, modern practice is to employ pads of the original form, i.e., the breadth of the pad radially equals its length on the mean diameter. It pivots on a radial line at the back and a little to the rear of its centre of figure relative to the direction of rotation of the shaft.

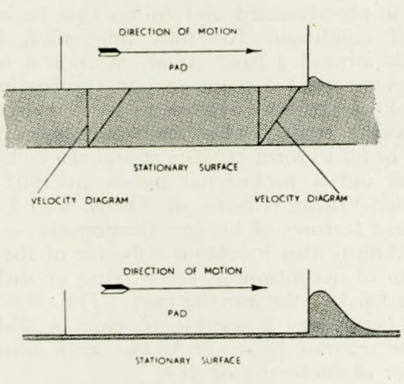

FIG. 10—*Diagram showing the effect of increasing the load on the pad when moving parallel to stationary surface*

Perhaps a greater appreciation of the thrust bearing can be derived from a closer consideration of the conditions necessary for sustaining the oil film between pad and collar. Suppose a surface is in motion relative to and parallel with a stationary surface (Fig. 10). Suppose also that the load on the moving surface is sufficient to allow an oil film to form. It is obvious that the velocity across the oil film tapers from a maximum at the moving surface to zero at the stationary surface. The velocity diagram is therefore the shape of a right angled triangle. If now the load on the moving surface is increased and the oil pressure remains the same, the oil will be squeezed out from between the surfaces, allowing contact to take place. To overcome this if one of the surfaces is tilted sufficiently relative to the other the hydrodynamic action of the oil will produce an oil film which will support and remain stable under the greater load. The velocities of the oil layers across the fluid film have been found to be something of the nature of those shown in Fig. 11. The oil entering at the leading edge is drawn along with diminishing thickness and leaves at the trailing edge; the quantity at exit would be the same as that entering except for losses incurred due to side and front leakage. The front leakage is represented on the diagram by a negative loop at inlet. The load carried by the bearing depends on the velocity of the moving surface, shape and dimensions of bearing surfaces and the viscosity of the fluid.

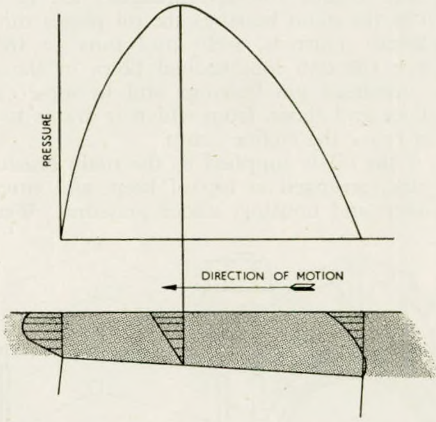

FIG. 11—*Diagram showing pressure and velocity of viscous flow between inclined surfaces*

Theory has shown that the best positions for supporting the loaded surface of a thrust pad, for least friction, is in the region of 0·4 times the length measured along the mean diameter from the exit edge. The pivot line or radial line lies between the points of maximum and mean pressures (Fig. 9).

A Michell thrust bearing is shown in Fig. 12. The thrust pads may either be arranged completely or partly around the collar on the thrust shaft. The ahead and astern thrust are transmitted from the shaft, through the two rings of pads A and B respectively, to the casing. During normal operation the pads tilt so as to take up a small inclination to the surface of the rotating collar in the direction of rotation. Lubricant is supplied under pressure by a pipe fastened securely to the cover. Suitable thermometers are fitted to indicate the temperature of the oil entering and leaving the thrust block. A baffle is arranged, as shown, to assist circulation.

Thrust blocks employing fixed tapers have been used by S. Z. de Ferranti and others from time to time. Fixed taper

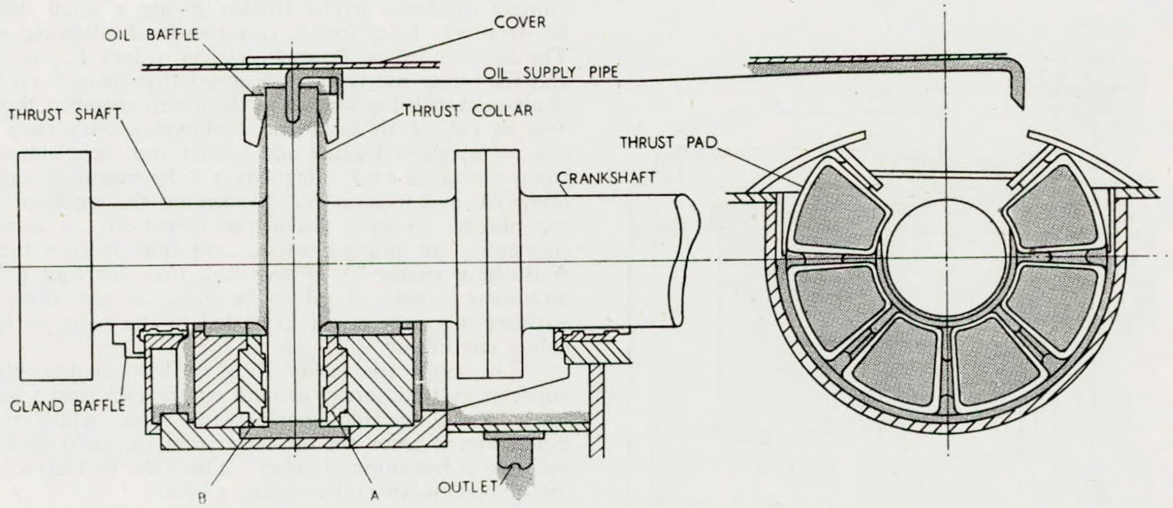

FIG. 12—*Section through Michell thrust block*

thrust bearings have been adopted for marine services quite successfully. A bearing of this type is shown in Fig. 13 and consists essentially of a shaft arranged with two collars to work in conjunction with a fixed shoe. This bearing, like Michell's, uses the principle of converging surfaces to generate an oil film between rotating and stationary members. The bearing is so designed that the oil film supports the imposed load with as little fluid friction as possible. The success of this bearing may be attributed to the accuracy with which the bearing surfaces can be machined and fitted. The thrust load of the prime mover of a ship at zero speed is negligible and increases from a small value at zero output to a maximum at or near maximum output at rated speed. This condition is ideal for the adaptation of the fixed taper thrust bearing, since the bearing can be accurately dimensioned to carry the normal load at normal revolutions.

This type of thrust block is usually incorporated in the engine bedplate and has a single fixed thrust shoe of ample dimensions to take the maximum thrust. The thrust shoe is lined with white-metal on both ahead and astern faces, suitably grooved and tapered to ensure efficient lubrication and cooling of the working faces. The cooling and lubricating oil is usually supplied from the engine forced lubrication system, and gunmetal gland baffles are fitted to prevent oil leakage at the shaft. The necessary thermometers are fitted.

The thrust shaft, arranged with integral collars and flanges, is made of forged ingot steel and is smooth-turned all over.

Diesel engine cylinders require to be most efficiently lubricated for the following reasons:—

(1) To reduce friction between the moving surfaces and hence reduce the power absorbed to overcome the work done against friction, consequently, obtaining a higher mechanical efficiency.

(2) To reduce wear between the piston rings and cylinder liner to a minimum.

(3) To produce a seal to prevent combustion gases leaking between rings and cylinder liner.

In early Diesel engines a small force pump was used to inject the lubricating oil into the cylinder. The supply pipe was connected from the discharge side of the pump to the admission points located on the cylinder liner wall. This pipe completely encircles the cylinder with branches led off to each of the oil points. With this arrangement, due to the oil taking the least line of resistance, parts of the liner surface were unequally lubricated, which gave rise to much uneven liner wear.

These and other deficiencies were eliminated by using a separate feed, from lubricator pump unit to each injection point, so that the quantity of oil issuing from any particular point could be varied at will.

The number of points at which oil is introduced to the liner varies considerably, the number nevertheless usually increases with increase of cylinder diameter; present practice

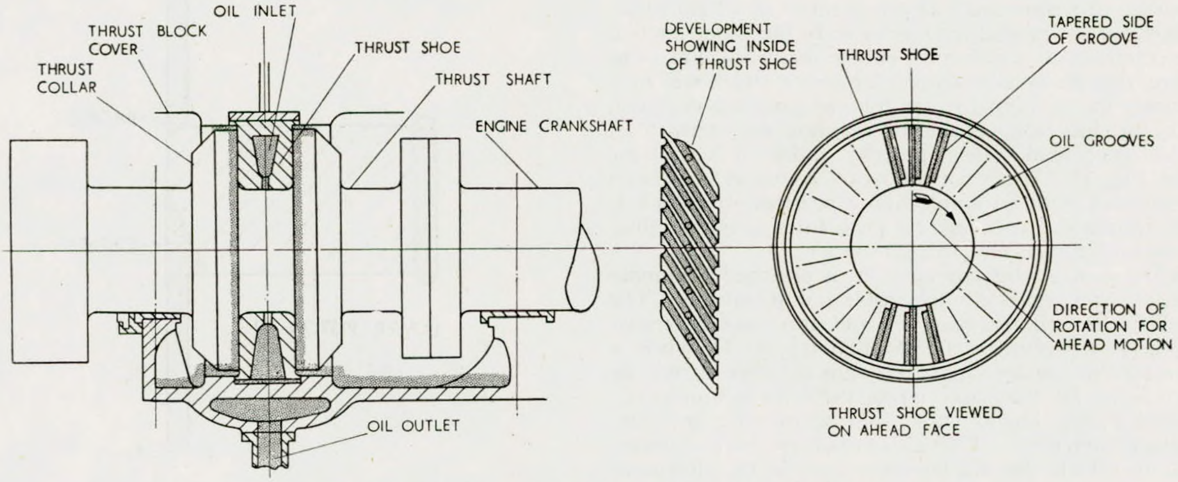

FIG 13—*Section through a Harland and Wolff type thrust block*

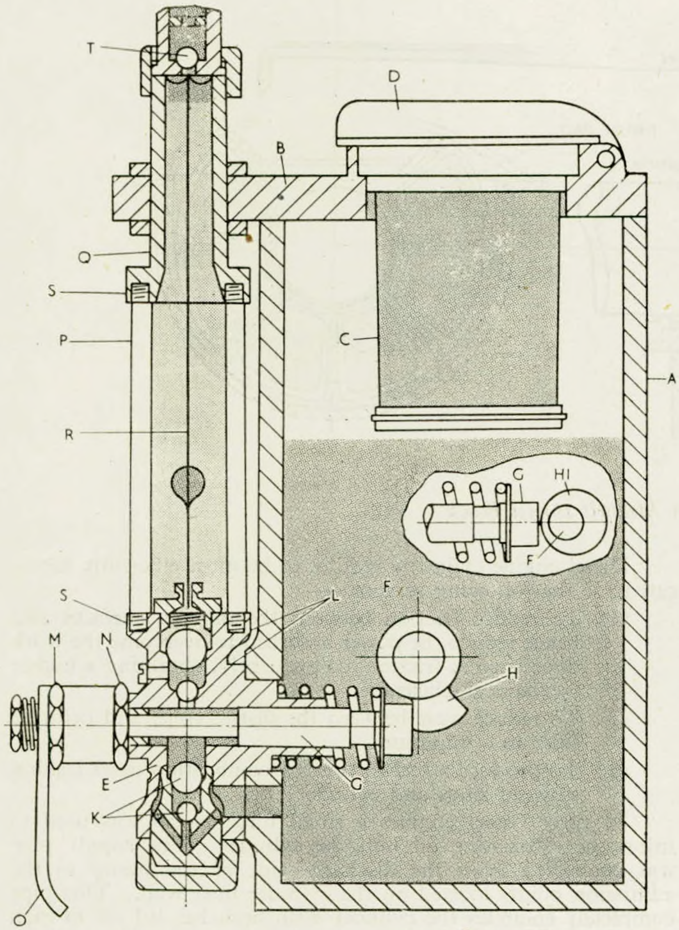

FIG. 14—*Section of level driven ("T and K") mechanical sight feed cylinder lubricator (J. and W. Kirkham type)*

is to have from between 2 to 6 points spaced around the circumference and in the same plane.

The factors determining the number of points used are the viscosity of the lubricating oil and the working temperature of the cylinder liner. To obtain the best results regarding cylinder wear, piston ring wear and sealing effect, the whole cylinder surface must have an oil film of the requisite thickness. This condition can be obtained by arranging a large number of points with a small injection of oil, or by providing a small number of points and a larger quantity of oil per injection. Experience has proved the former to be the better method and is the condition at which most engine designers aim. The obstacle here, though, is to produce a lubricator which will produce effectively the oil supply in the minute quantities required, and also to produce one capable of accurate adjustment. A pump which has gained great popularity, and is in general use is shown in Fig. 14. It consists of an oil container A, with a cover B, provided with an ample filling aperture, in which is arranged a strainer C. A hinged lid D, is fitted over the filling hole thus excluding dust and foreign matter.

Along the front of the container A, is arranged a number of independent and separately detachable pump units E. The drive is taken through the shaft F, and this may be transmitted to the pump plungers G, through tappets H, where a simple direct reciprocating drive is required (lever drive), or through eccentrics H1 (see inset) where the drive is rotary, i.e., through band pulley, chain wheel, spur gears, etc., or intermittent rotary (ratchet). The differential or two diameter plunger G, in which the displacement area is the difference between the areas of the larger and smaller diameters, enables a small effective displacement to be given with a substantial plunger diameter, whilst further giving a small displacement for relatively long stroke, and thereby facilitating regulation. The suction valves K, and delivery valves L, are duplicated and the pump has been so designed that there is no possibility of air-pockets being formed in the pump chamber, thus eliminating all risk of air locks and cushioning, with their attendant evils of irregular feeding and partial and, very often, complete stoppages of oil feed. Regulation is by means of the regulator screw M, and locknut N. Slackening the regulator M, draws the plunger G away from the tappet H, or eccentric H1, shortening the plunger stroke, and thus reduces the oil feed. A flushing trigger O, is provided, thus enabling a temporary additional supply of oil to be given at any time, and also enabling a supply of oil to be fed to the point of application before starting up.

The sight feed glass P is of best quality glass, triple annealed and accurately ground on the ends and together with its holder Q provides ample water space, whilst the globule guide wire R keeps the oil away from the sight feed glass and prevents it becoming clouded. The sight feed glass joint rings are of best quality oil-resisting rubber.

A non-return valve T is included in the union outlet connexion preventing the supply pipe from becoming empty when the feed pipe is disconnected at the lubricator end.

At the delivery end of the oil supply pipe there is a non-return valve. This small spring-loaded ball valve prevents the lubricating oil entering the cylinder at times other than when the pump is delivering, and maintains a full supply pipe, particularly when the engine is at rest, thus ensuring an immediate oil supply to the cylinder when the engine is started.

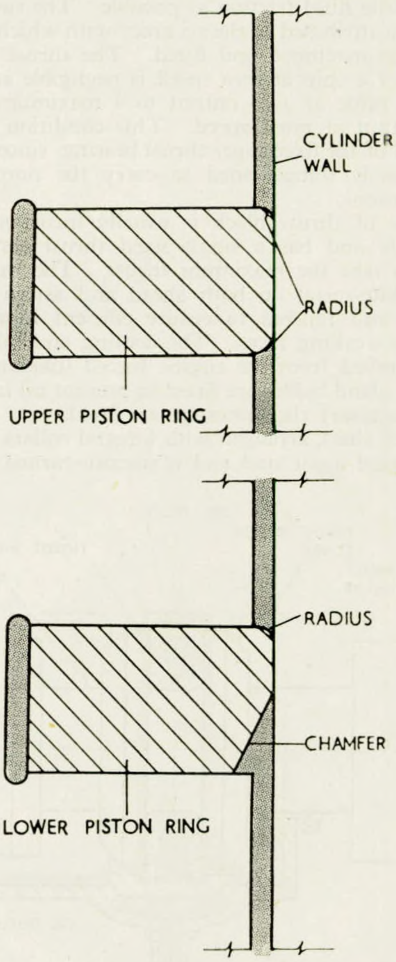

FIG. 15—*Piston rings radiused and chamfered to facilitate the formation of oil film*

In some cases the injection holes are spaced equally round the circumference of the liner, while in others they are grouped near the ends of a diameter drawn from back to front.

The lower the viscosity of the oil used at the working temperature the more readily will it spread over the rubbing surfaces, so that the less viscous the oil the further apart may be the points at which it is introduced and *vice versa.* There is, of course, a limit to the minimum viscosity of the oil, since, should it be too thin, it will readily be swept out of the cylinder by the piston on the down stroke before it has had an opportunity to spread.

To assist the spreading of the oil on the surface of the liner, oil grooves have been used with considerable success. Oil grooves properly arranged on the liner surface greatly aid distribution, in so much that the annular spaces formed between piston, piston rings and cylinder liner surface have an adequate oil supply. It will be easily appreciated that these annular spaces are by far the greatest distributing agents, and extensive use is made of this fact. Nevertheless, there are many designers who hold the opinion that the cylinder liners should have a smooth unbroken surface in order that the oil film should not be disrupted.

The location of the injection points for four-cycle single acting engines is usually between the two uppermost rings when the piston is at the lowest point of its stroke. In double acting engines the oil is normally introduced at mid-length, the usual arrangement being such that the injection holes are never uncovered by the piston.

The efficient lubrication of two-cycle engine cylinders is a more complex matter, owing to the cycle of operation tending to produce higher temperatures. The use of scavenging air ports, and in some cases exhaust gas ports, has made it extremely difficult to prevent some of the lubricating oil from escaping with the exhaust gases. Oil scraped over the scavenge ports, by the piston as it traverses the cylinder, is another source of trouble, and effective means are provided for draining the oil which enters the scavenge belt, in order to prevent scavenge fires. It appears, from practice, that the recommended position for oil injection is between the two lower piston rings when the piston is at top dead centre. The oil entering at this point is not likely to reach the lower portion of the cylinder, but these nevertheless are usually adequately lubricated, as in most engines of this type the piston skirt enters the crankcase every revolution and picks up ample oil to lubricate this part efficiently.

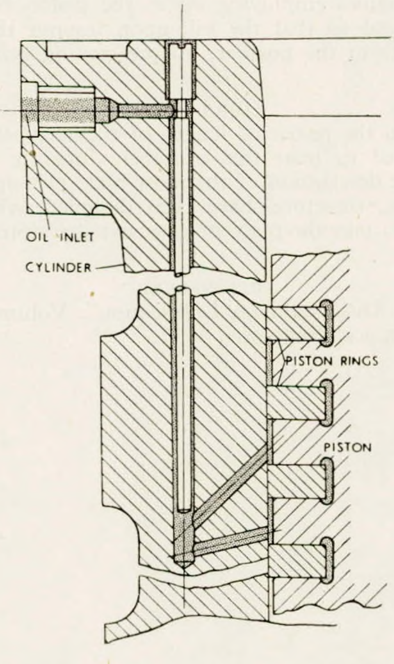

FIG. 16—*Fosby's lubrication system for cylinders*

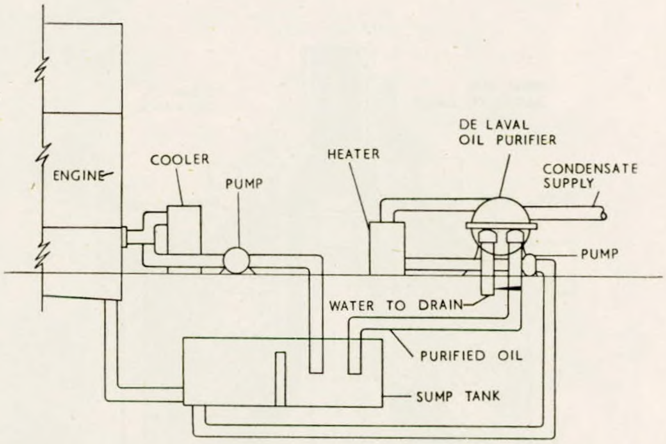

FIG. 17—*Installation for the continuous by-pass purification of Diesel engine lubricating oil*

A method devised to take advantage of the annular spaces between the piston rings, being the best means for distributing oil, is shown in Fig. 15. In cylinder liner lubrication it is not possible to obtain "fluid film" conditions, but by chamfering the bottom edges of the piston rings, as shown, it is possible to induce the oil, carried in the annular spaces, to escape readily and so produce an oil film of reasonable thickness on the cylinder liner when the piston is on the downward stroke. It will be seen also that the larger chamfers on the lower rings permit the oil to flow readily to the upper annular spaces, formed between the top piston rings. This is extremely desirable, because it ensures a good supply of lubricating oil to the upper part of the cylinder, which is the part most subjected to wear.

Attempts have been made to time the discharge of oil into the cylinder to take place immediately the piston is in a particular position, so that the oil is directed between the piston rings, but it is doubtful indeed whether this has ever been achieved because of the difficulty in calculating the time lag between lubricator and cylinder point. The time lag is the interval of time which elapses from the moment the lubricator discharges, to the instant injection into the cylinder begins.

An interesting design to overcome the timing problem is shown in Fig. 16. With this arrangement the lubricator discharges the oil into one or more oil reservoirs in the liner wall, which communicate with the liner surface through two small holes at a suitable angle. The small holes are pitched a little greater than the pitch of the piston rings. No oil grooves are cut in the cylinder liner surface. When the piston passes the holes the difference of pressure on the upper and under sides of the piston rings blows the small quantity of oil in the reservoir into the clearance space around the piston. The two small holes from the oil reservoir are placed on a level with the two lowest piston rings when the piston is at top dead centre. There is then a suitable pressure for blowing in the oil and the uppermost part of the cylinder liner which is mostly exposed to wear is ensured a continual supply of oil.

Efficient purification of Diesel lubricating oil is of paramount importance to ensure good performance and long service life of the engine.

The general arrangement of a typical lubricating oil purification installation employing a De Lavel centrifugal oil separator is shown in Fig. 17. It will be seen that the lubricating oil is pumped from the lowest part of the sump tank through a heater to the centrifugal purifier, where the oil is freed from abrasive impurities, carbonaceous sludge and water, and returned to the tank. The returned oil may be passed through a cooler if required. The engine lubricating oil pump draws the oil from the sump tank and discharges through a cooler to the engine. Having circulated the engine the oil

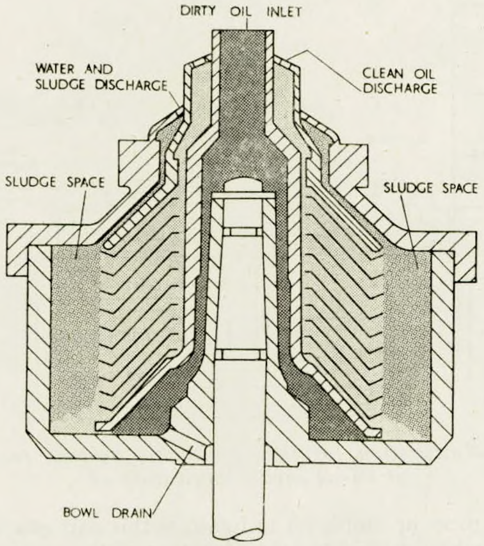

FIG. 18—*Cross-section and flow design of the De Laval centrifugal oil purifier*

drains by gravity from the engine sump to the sump tank. The section, see Fig. 18, through the separator bowl shows how the oil, sludge, etc., separates when the bowl is rapidly rotated. The oil entering the separator bowl must of necessity be within certain temperature limits, to facilitate complete separation, and the heater is rated accordingly.

Fig. 19 shows another typical Diesel lubricating oil purification installation embodying a Sharples super-centrifuge. This arrangement is also a continuous by-pass principle, similar to that previously mentioned, and the figure is self explanatory. A section through the centrifuge is shown in Fig. 20, and it will be seen that, as before, due to the centrifugal action on a mixture of two liquids containing suspended solids heavier than the liquid, the liquids take up the positions shown and the solids are held within the bowl. The liquids pass continuously through the bowl, and are discharged separately.

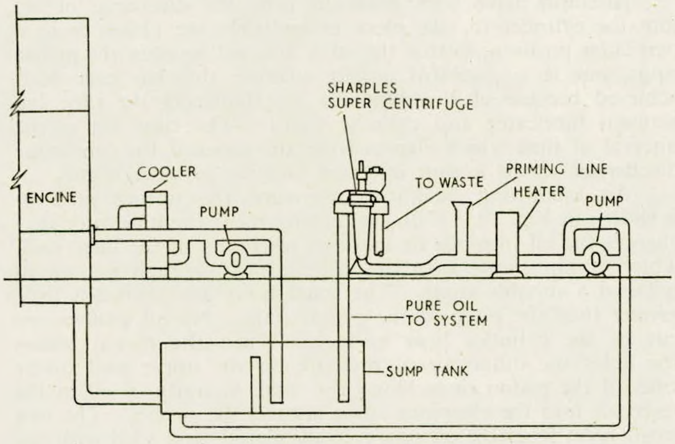

FIG. 19—*Installation for the continuous by-pass purification of Diesel engine lubricating oil*

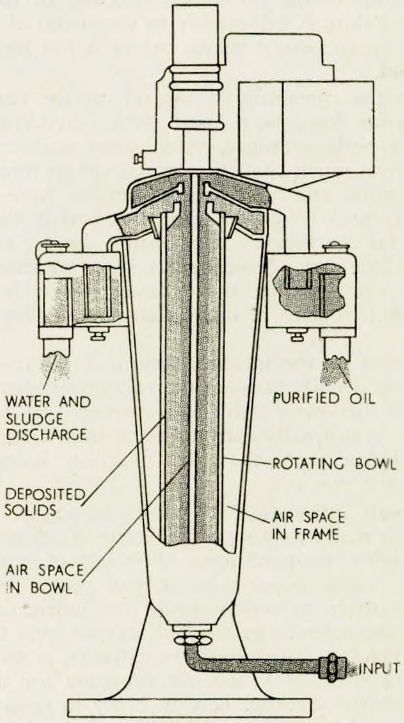

FIG. 20—*Cross-section and flow design of the Sharples "Vaportite" super-centrifuge*

Diesel engines employing oil as the piston cooling media can be arranged so that the oil, upon leaving the pistons, is passed directly to the purifier, no pre-heating being necessary.

### CONCLUSION

Owing to the restricted length of the essay, the writer has been compelled to treat this extremely intricate subject with an inadequate description of the most basic principles involved. The diagrams, therefore, have been designed, where possible, with a view to take the place of extensive descriptive writing.

### REFERENCES

"General Discussion on Lubrication", Volume 1, Institution of Mechanical Engineers, 1937.

# INSTITUTE ACTIVITIES

## MINUTES OF PROCEEDINGS OF THE ORDINARY MEETING HELD AT THE INSTITUTE ON 28TH SEPTEMBER, 1950

An ordinary meeting was held at the Institute on Thursday, 28th September 1950 at 5.30 p.m. The Chairman, Mr. G. Ormiston (Chairman of Council) in opening the meeting said:

"This is the first meeting of the session, and we are delighted to have with us our President, Sir Murray Stephen, who is to read his Presidential Address.

To most Marine Engineers Sir Murray is no stranger, and the name of Stephen is a household word in shipbuilding and engineering. He is one of the sixth generation to be in charge of Messrs. Alexander Stephen's Shipyard at Linthouse, and I should think that this is a record. In these days of combines and big business, it is almost unique to find a family concern which has lasted so long. I have the pleasure of knowing our President's elder son, and you will all be pleased to know that the Stephens' innings is by no means finished, as there as still some Stephen batsmen in the pavilion!

You have before you a copy of the Presidential Address, which includes an outline of the career of our President, and you will all agree that Sir Murray is nothing if not versatile! He played as Captain of his College Rugby XV, and also rose to international status at hockey. In the early part of the 1914-18 War, our President went to France, was mentioned in despatches, won the Military Cross, and was taken prisoner. Since his return to this country he has held and is still holding numerous important positions in shipbuilding and other industries, and last, but not least he has honoured us by becoming our President.

I have much pleasure in asking Sir Murray to read the Address".

The President, Sir A. Murray Stephen, M.C., B.A., then delivered his Address (see p. 339).

In proposing a vote of thanks to the President, Mr. Ormiston said:

"I think you will agree that we have had a very interesting Address from our President, and I am rather sorry that it is not open to discussion, as I am sure that there would be some worthwhile comments.

Sir Murray has once again made a point of reliability, and I repeat the words I used on the occasion of our last Presidential Address, that reliability is the most important word in a marine engineer's vocabulary.

Our President also mentioned that the margin left for improvement in efficiency is manifestly becoming smaller, and to achieve higher economy the cost is rising. Steam machinery, can, at a price, continue to improve in overall efficiency, but it is questionable whether reliability can be maintained, due to the additional complications involved. On the other hand, Diesel economy has varied little over the past twenty years, with one notable exception which has taken place in the last three years. I refer to the equipping at a moderate cost, of a number of motor vessels to burn boiler oil in the main engines. This, in my opinion, is the most revolutionary change which has taken place for a long time. The difference in cost between Diesel and boiler fuel in Curaçao and Aden is approximately £2 to £2 10s. 0d. per ton in favour of boiler fuel, and the resultant saving in bunker costs of £100 to £150 per day in a vessel burning 50 tons per day cannot be disregarded.

Sir Murray has commented on the future trend in marine machinery, and stated that the internal combustion engine is a strong competitor of the steam engine, whether reciprocating or turbine. This is quite true, but up to the present there are no signs that the Diesel engine will approach the powers reached by steam even with multiple engines. To make further advances the gas turbine and atomic energy machinery come into the picture. Our President has summed up the gas turbine by saying that it has still some way to go, and I think it is agreed that the time has not yet come when it can be adopted generally for marine propulsion.

Regarding the tonnage laws, we are still hoping that one day we will be allowed to use less than 13 per cent of the gross tonnage without being penalized. Knowledge of the atomic energy ship is in the hands of a very few men, and I think I can safely say that very little has reached this Institute. However, if the bunkers are to be carried in a suitcase, I would suggest that a spare suitcase of bunkers be carried in case the original is mislaid!

We are all very interested in our President's outlook on funnels. It is evident that Sir Murray is speaking as a shipbuilder and not as a shipowner, or even one of the shipowner's office staff! I would say that the funnel receives more criticism than any other part of the ship, and if it is not exactly the right shape, with the correct rake and height, then there are many adverse comments.

My office looks out over the Royal Albert Dock, and it is nearly safe to say that no two ships have the same design of funnel. I have also noticed that ships on arrival whose funnels are painted with a light coloured paint are invariably dirty on top at the after end, showing that the smoke or gases have curled down towards the deck. In spite of the curious shaped funnels we set today, and after reading papers and articles on the subject, I am in full agreement with our President that the tall funnel is the only answer, to avoid smuts on the boat deck and dirty paintwork.

I am sure that Sir Murray's remarks on streamlining have given us all food for thought, and as I have already said, if the Address were open to discussion, there would be a number of members anxious to speak on this subject.

I think we all agree with our President in his remarks on welding. Numerous Diesel engines are at present giving good service with welded bedplates and entablatures, and many turbines are constructed with welded casings and gearcases, and we are pleased to learn that the fabricated structure is regarded favourably by builders.

Members will be interested in Sir Murray's remarks on the rising cost of ships, compared with the pre-war period. It is quite true to say that no owner builds a similar ship to the previous one, and I think this applies particularly to machinery. From the ordering stage to the time of delivery of a new ship, a period of approximately two years elapses, and during that time new ideas and improvements to main and auxiliary machinery come to light which are embodied in the next ship. I cannot see that this state of affairs will alter in the future, or should be allowed to, if we are to keep our place in the forefront of ship and engine design. In this connexion our President's remarks on the research organizations in this country are of particular interest. It is only by experimenting that progress will be made, and in my experience shipowners are only too willing to try out any new idea, or collect any data from ships at sea, which may be useful to research.

With regard to the *Lucy Ashton,* many of us I am sure have landed at the Tail of the Bank when coming ashore from trials in that old paddle tug, and we never visualized or dreamt that one day she would be propelled by aeroplane jet engines.

I think, Sir Murray, that most of your audience are very intrigued with the last sentence in your Address 'No one has yet found a suitable substitute for a wrought iron boiler tube'. Personally, this has never entered my head, but I could not agree with you more. The boiler tubes we are using today leave a lot to be desired, and who knows, perhaps your closing remark will bear fruit.

As Chairman of Council, it is my pleasant duty to propose a very hearty vote of thanks to Sir Murray Stephen for agreeing to be our President, and for reading his Address. I call on Mr. Turnbull, Vice-Chairman of Council, to second this proposal".

Mr. J. Turnbull, O.B.E. (Vice-Chairman of Council) in seconding the vote of thanks said:

"Sir Murray has, in the opening paragraph of his Address, stated that we have done him a great honour in asking him to become our President. He has done us an even greater honour in accepting. Perhaps it is due to modesty on his part or to our Secretary not having scrutinized the records thoroughly, as the printed statement of his career makes some quite important omissions; for instance Sir Murray is a member of the Committee of Lloyd's Register and some years ago he held, with distinction, the chairmanship of the Technical Committee of the British Corporation, a position which he was well qualified to hold, quite apart from his natural attainments, for he was at one time on the technical staff of that society.

I am sure that the members of this Institute are proud to have for their President one who has been trained as an engineer and naval architect and has reached such a high position in industry. Sir Murray and his forebears have done as much as anyone to maintain the very high reputation which shipbuilding and marine engineering in this country hold throughout the world.

Our President's Address brings to mind the old Scotch saying 'Short rede is guid rede' which translated into English, not for the benefit of our President but for others present here tonight, means 'Short council is good council'. He has within two pages dealt most efficaciously with about twenty different important subjects ranging from the dimensions of funnels to nuclear energy. I would forewarn anyone who may be thinking of crossing swords at some later date with Sir Murray on any of his statements that he is a most active member of the British Shipbuilding Research Association, an Association which has made excellent progress during the short time of its existence under its able Council, of which he is Chairman and its Director of Research. Sir Murray's statements, although simple in appearance and devoid of highly technical nomenclature, are supported by research and by hard practical common sense. It is most satisfactory that we shall have this Address recorded in our TRANSACTIONS.

I think I need say no more, save to second in the warmest terms the vote of thanks so ably proposed by our Chairman of Council".

A vote of thanks was accorded with acclamation.

The President, responding, thanked the Chairman, the Vice-Chairman and the members for their very warm vote of thanks. The writing of a Presidential Address was a rather difficult task, because its presentation was one occasion when the author's subject matter could not be criticized. Therefore he had, with impunity, put in a few things which he felt would meet with disagreement and hence some of his rather provocative remarks on the present trends. Some years ago he had had to make a Presidential Address and he had decided that there was one subject which he thought people would be longing to discuss—tonnage measurement—and he had got away with it! Some of these things in his Address were worthy of discussion later on and they might have repercussions. Mr. Turnbull had made one remark about shipbuilding research and putting things in nice simple language. He, Sir Murray, was always stressing the importance of recording the B.S.R.A. findings in simple, plain English, not in too technical language. He thought that many authors of papers might improve on them in this way, and he had endeavoured to carry out his own precept in this respect.

Finally, he would like to say how much pleasure it had given him to come to the Institute and deliver this Address.

The meeting then terminated at 6.15 p.m., there being fifty-one members and visitors present.

# JOINT PAPER

read before

THE INSTITUTION OF NAVAL ARCHITECTS *and*
THE INSTITUTE OF MARINE ENGINEERS

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## FUNNEL DESIGN AND SMOKE ABATEMENT

### Part I

### THE CAUSES OF SMOKE POLLUTION AND POSSIBLE METHODS OF PREVENTION

By E. OWER, B.Sc., A.C.G.I.*

### Part II

### EXPERIMENTAL TECHNIQUE

By C. H. BURGE†

*Read in London on April 25, 1950, Mr. G. Ormiston (Member of Council I.Mar.E.) in the Chair, supported by Mr. L. Woollard, M.A. (Vice-President I.N.A.)*

### Summary

**Part I.**—The causes of the descent of smoke on to the deck are explained, and it is shown that the trouble can be avoided either by increasing the height of the funnel, or by imparting enough upward momentum to the funnel gases to carry them into the smooth flow of air above the disturbed, eddying zone immediately over the deck and superstructure. Momentum can be given either by speeding up the funnel gases themselves or by blowing additional air out of the uptake; this air need not be passed through the boilers. The best shape of funnel is cylindrical, because the conventional streamlined casing is no longer streamlined in winds inclined at more than 10 deg. or so.

Other possible methods of improving conditions are discussed, including a recently patented French funnel which seems to be promising.

**Part II.**—The experimental technique by which the problem is studied with models in the wind tunnel is described, and the results are discussed. One of the methods of prevention hitherto investigated on the model scale only consists of surrounding the gases from the uptake with an annular sheath of high-velocity air.

## PART I

### Introduction

There is little doubt that aesthetically the modern ship, with its short, raked, streamlined funnels, is much more satisfying in appearance than the ships of some twenty or thirty years ago, in which high, spindly, cylindrical funnels were the general rule. There is equally little doubt that this change in funnel design is mainly responsible for the trouble that occurs so much more frequently to-day, namely the descent of fumes, smoke and soot on to the deck.

The problem has received a good deal of attention during the last ten years or so, both for naval and merchant ships; and, in July of last year, the British Shipbuilding Research Association issued a survey of existing knowledge on the subject to its member firms. This survey was prepared by the author of Part I of this paper, who has been given permission by the Association to make use of it here.

The cause of the trouble is essentially aerodynamic in nature and associated with the flow of air over the superstructure of the ship and around the funnel. Many cures have been suggested, some partly successful, others not; and it is true to say that no successful one has yet been devised which is free from all objections. It is, indeed, difficult to see how such a remedy can be found, short of a reversion to the high, cylindrical funnels of the past.

### General Statement of the Problem

In general, the funnel exhaust is partly gaseous and partly solid. The solid matter, consisting of particles of soot or ash large or dense enough to have an appreciable velocity of descent in air, provides a special problem about which very little can be done, except to prevent it from being formed or to remove it from the exhaust before it is discharged into the air. Once these particles are ejected, they must fall on to the deck, if their natural velocity of fall is high enough to cause them to drop the necessary distance before they are carried clear of the ship by whatever horizontal speed they can pick up from the relative wind. The special case of these larger particles is discussed later; the main problem is that of the gaseous products of combustion, and of the small

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* Intelligence Officer, British Shipbuilding Research Association.

† Senior Experimental Officer, National Physical Laboratory.

particles forming the smoke proper whose behaviour can be considered for the present purpose as essentially the same as that of the gases.

The path of the smoke trail from a funnel *of given shape and size* is determined mainly by four variables, namely:—

(*a*) The speed of the relative wind.
(*b*) The speed of emission of the smoke.
(*c*) The density (weight per unit volume) of the smoke.
(*d*) The form of the superstructure ahead of the funnel, and, to a smaller degree, the form of the bows and the superstructure aft.

Strictly, another variable should be added to this list, that is the direction of the relative wind, but this can be regarded as equivalent to a change in variable (*d*), and so can be discussed under that head.

It should be repeated that these four variables relate only to a funnel of given shape and size; any change in the form of the funnel introduces another important variable which will be considered later. Associated with it is again the effect of a change in the direction of the relative wind, which, except for a vertical, cylindrical funnel with an unraked top (for which there is no such effect), can be regarded as equivalent to a change in shape of the funnel.

Restricting ourselves for the time being to a particular funnel, that is, neglecting the effect of changes in funnel shape, we can perhaps most easily form a conception of the behaviour of the smoke trail by considering firstly the simplest case in which only variable (*a*) operates, and then showing how the other variables modify this behaviour. We start, therefore, with a funnel rising from a flat deck, and assume no obstructions for a considerable distance forward (i.e. negligible effect of bows and superstructure), small velocity of emission of the smoke, and density of smoke not appreciably different from that of the atmosphere. Even in a slight wind, the smoke trail would then be horizontal,* and, were it not for the low-pressure region behind the funnel, the lower edge of the trail would be level with the top of the funnel. But this low-pressure region causes the smoke to descend below the funnel top: in effect, as far as the smoke trail is concerned, the funnel top is somewhat below the actual top. This is shown by the lighter smoke trails in Fig. 1, which is a photograph of the smoke from a group of tall, cylindrical power-station chimneys. There is evidence also of the effect of eddies shed by the chimneys, which cause occasional puffs of smoke to descend well below the main trail. Further reference to Fig. 1 will be made later under the heading of funnel shape. For the present, we need only remember that the funnel behaves as though its true or "effective" height were less than its real height, and we can neglect the effect of the low-pressure region behind the funnel if we speak of effective top or effective height instead of real top or real height.

We see then that, for the simple conditions postulated (i.e. no obstructions ahead and negligible velocity of emission and differences of density), the lower edge of the horizontal trail from the effective funnel top represents a boundary below which the smoke does not fall appreciably; but any departure from these conditions will alter the path of the smoke trail. Thus, the path will obviously be raised by the upward momentum of the funnel gases if there is any appreciable velocity of emission [variable (*b*)]; and, because of the relatively high temperature of the gases [variable (*c*)], their density is in practice always below that of the air, and this again raises the trail.

That the effect of temperature can be quite substantial is shown by the difference between the dark and light smoke trails in Fig. 1. The light, dense trails come from chimneys emitting "washed" smoke from which most of the solid matter has been removed, and the efflux consists very largely of condensed steam, which is considerably cooler than the dark, unwashed smoke coming from the third chimney. It will be seen that the darker smoke trail is distinctly higher, despite the fairly high natural wind that was blowing at the time the photographs were taken.

Thus we see that, of the four variables, (*a*) by itself produces an approximately horizontal trail, while (*b*) and (*c*) will always act in the sense of an improvement by causing the gases to rise, if even slightly, above this horizontal limit. Whenever trouble occurs from the descent of smoke and gases abaft the funnel, it is due† to variable (*d*), i.e. the form of the bows and superstructure, particularly in its relation to the position of the effective funnel top. How this occurs is explained in the next section.

### The Effect of Obstructions

When a wind strikes a bluff obstacle projecting from a flat surface, it is deflected upwards by the top edge in the manner sketched in Fig. 2. Above a certain line A B C, the air continues to flow smoothly, almost as though A B C were the boundary of the bluff obstacle. Eventually, the line A B C returns to the level of A D, the top of the obstacle, and then falls below it if A D is shorter than A C; but this occurs at a distance from A which, in cases of practical interest, is several times the height of the obstacle. The space A B C D between the line and the top of the obstacle is filled with violent eddies; and the line A B C therefore represents a boundary, which we shall call the turbulence boundary, between regions of smooth and disturbed flow. The course of the line A B C can be changed considerably by alterations in shape of the obstacle, particularly by relief of the sharpness of the top edge by means of curves or chamfering;[1] but, in general, whenever a bluff obstacle is exposed to a wind there is a region of eddying flow above it, separated from the smooth flow by a fairly well-defined boundary.

Any structure, such as a deckhouse or bridge, erected on the deck of a ship meeting a head wind, constitutes a bluff obstacle from which a turbulence boundary springs. The bows themselves form another obstacle: if the wind is dead ahead and the bows are flared, the disturbance introduced into the flow is more lateral than vertical, and comparatively little eddying results over the deck forward of the superstructure; if, however, the wind is inclined, the bows act as a bluff obstacle and there may be large eddies over the deck.

If smoke from the funnel enters the general flow well above the turbulence boundary it will not descend to deck level before the boundary reaches that level; but if it is introduced below the boundary it will come within the influence of the eddies, and may reach the deck anywhere aft of the funnel, or, indeed, even forward of it. The three photographs of Fig. 3, which have been provided by Mr. Burge, who describes the experimental technique in Part II, show the turbulent zone on a model ship. Fig. 3(*a*) shows the appearance of the smoke trail in a free stream; for this experiment the smoke was introduced well to the side of the model, and was clear of the disturbance it caused. For Fig. 3(*b*), the smoke was introduced in the central vertical plane just below the level of the turbulence boundary springing from the superstructure; the smoke is drawn down by the eddies and fills the space behind the funnel almost completely. Fig. 3(*c*) shows similar conditions with the funnel removed. It should be noted that the separate eddies apparent in the instantaneous-exposure photographs of the power-station chimneys (Fig. 1) are not seen in Fig. 3 because the latter photographs were given time exposures, as described by Mr. Burge.

It follows from the foregoing that the smoke must be discharged well into the smooth flow above the turbulent zone if we wish to be certain that the smoke will not descend to deck level before the turbulence boundary, which generally occurs well beyond the stern of the ship. To reach this favourable point of discharge we can either make the funnel

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* The relatively small spread due to natural diffusion is neglected.

† Apart from the effect of funnel shape, for which see later.

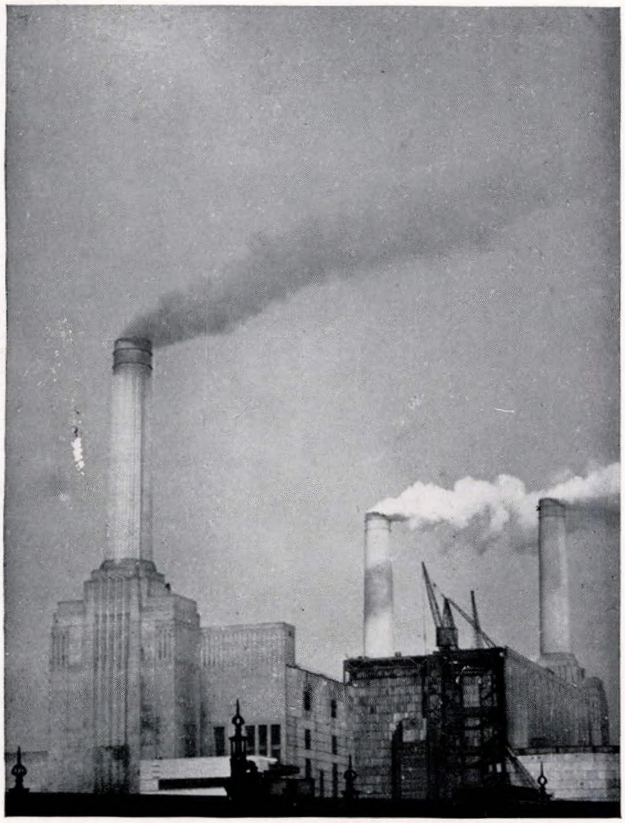

FIG. 1

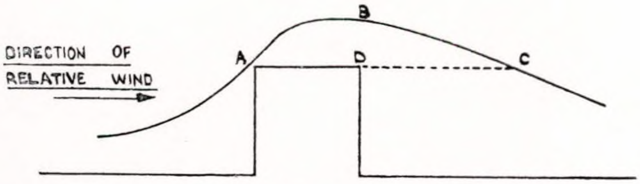

FIG. 2

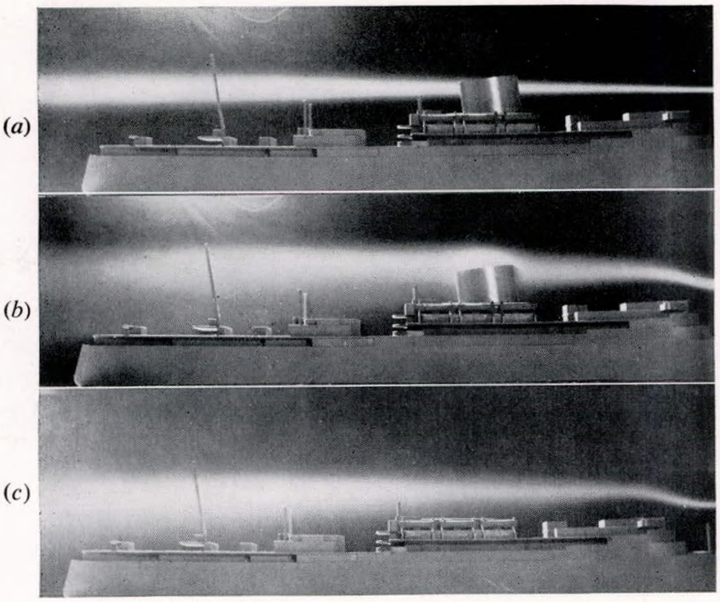

FIG. 3

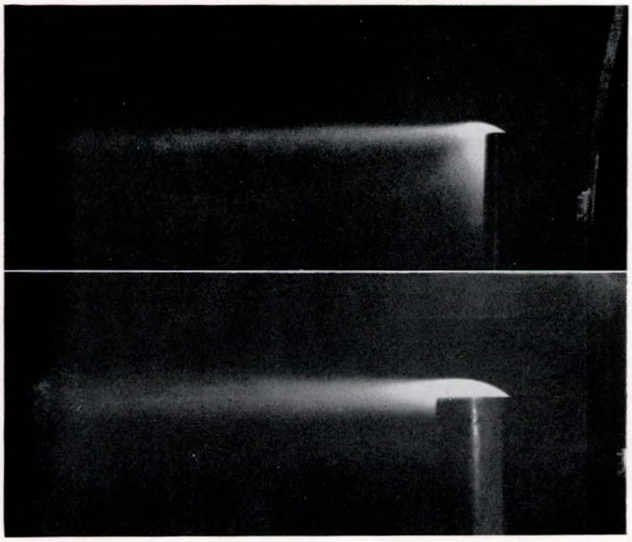

FIG. 4.—THE EFFECT OF A STREAMLINED FAIRING PLACED AROUND THE FUNNEL
Velocity ratio $s/v = 1/1$.

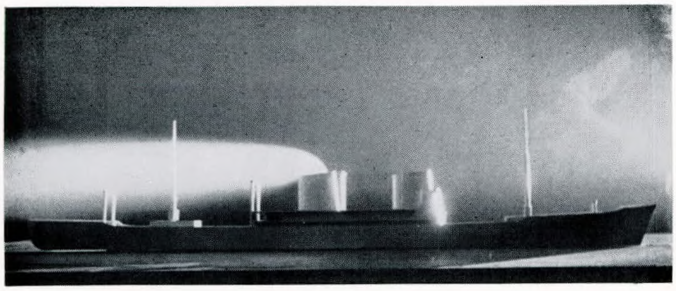

Fig. 6

Fig. 7

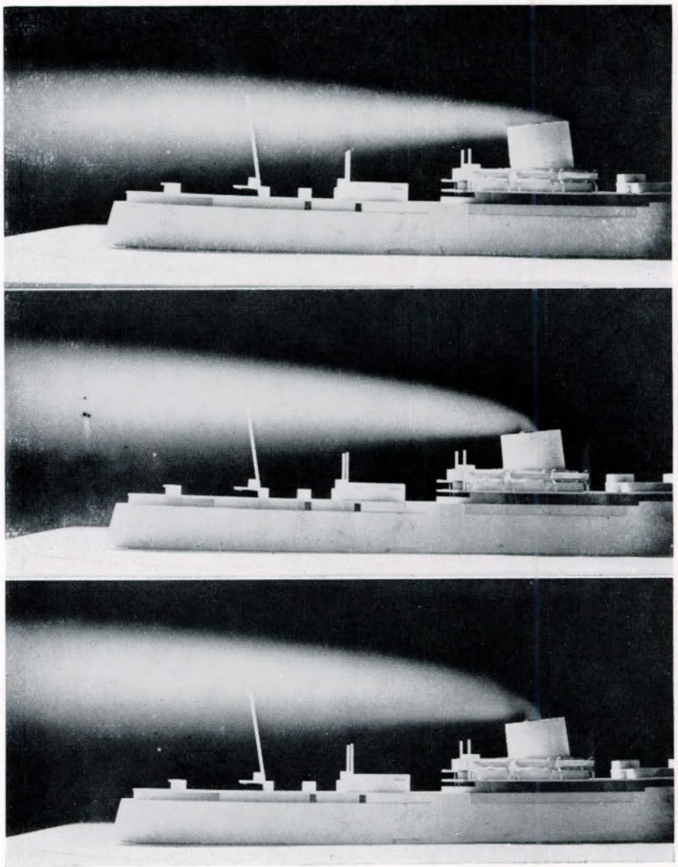

Fig. 9.—The effect of an annular air jet around a funnel uptake in the centre of the funnel casing

Velocity ratio $s/v = 1/2$.

*Top*—Normal funnel.
*Centre*—Normal height reduced 9 ft. Jet velocity $= 2 \cdot 5\ v$.
*Bottom*—Normal height reduced 9 ft. Jet velocity $= 4 \cdot 0\ v$.

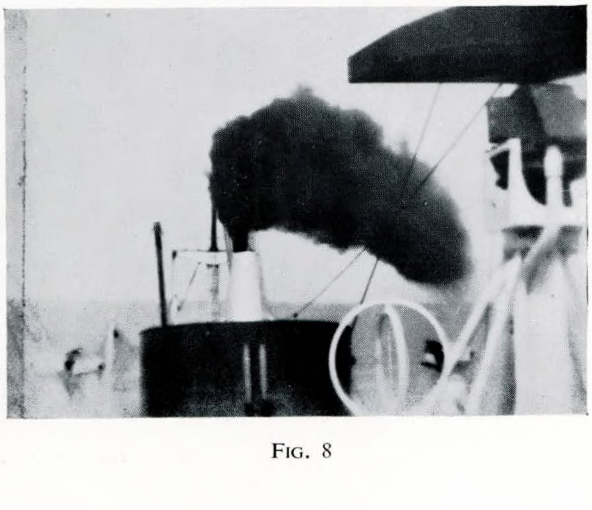

Fig. 8

sufficiently tall, which, in modern ships, may entail a considerable increase in height, or we can give the smoke from a low funnel enough upward momentum to carry it above the turbulent zone.

### The Efflux Velocity of the Funnel Gases

The upward momentum of the funnel gases can be increased for a given uptake diameter by increasing either their temperature or their velocity, but the first alternative is so much more wasteful in power than the second that it need not be considered. The amount by which the momentum of the funnel gases must be increased to effect an improvement in any particular case will obviously depend on the horizontal speed ($v$) of the relative wind. If, therefore, we increase the momentum by increasing the vertical efflux velocity ($s$) of the smoke, the significant quantity is the ratio $s/v$.

Numerous experiments have been made in this country mainly at the National Physical Laboratory, and by Nolan[2] in America, on the effect of varying this ratio. These experiments show that when the ratio is equal to about 1, the axis of the smoke plume from a cylindrical chimney discharging into free air is roughly horizontal, and that the plume is raised appreciably when the value of the ratio is about 2.

### Shape of Funnel

*(a) Wind Ahead*

The minimum amount by which the real funnel top must protrude above the turbulent boundary to ensure freedom from the smoke nuisance depends to a considerable extent on the shape of the funnel. It has already been stated that there is a low-pressure region behind the funnel, which causes the smoke to be drawn down below the top (see Fig. 1). The height depends largely on the shape of the funnel, as can be seen from the photographs of Fig. 4. The object in the upper photograph is a model cylindrical funnel emitting smoke in a wind tunnel, and it will be seen that the smoke is sucked down immediately behind the funnel to a distance of more than half the height. The difference between this photograph and those of Fig. 1 is partly due to the fact that the long duration of the exposure for the model funnel gives an exaggerated impression of the amount of smoke behind it at any given instant. The essential feature about this photograph, however, is the difference between it and the lower one, which was produced by placing a streamlined sheet-metal casing around the cylinder; the breadth of the cross-section of the fairing was just enough to enclose the funnel, and its length along the wind direction was about four times the breadth.

The great improvement due to the streamlining with wind ahead is apparent from these photographs: the intensity of the suction behind the funnel is much reduced and the smoke trail is correspondingly less depressed.

Another factor that influences to some extent the path of the smoke trail is the shape of the top of the funnel. We know, for example, that a raked top is bad. This is shown diagrammatically in Fig. 5, which gives the approximate paths of the smoke plume from a typical streamlined funnel under various conditions. In Fig. 5A the wind is dead ahead, and the effect of the rake is to cause an eddy as shown above the funnel and a break-away of the flow from the forward edge. The lines (*a*), (*b*), (*c*) and (*d*) represent approximately the paths that would be followed by streamers attached at the points from which the lines spring. In passing, we may note that experiments have shown that spaces between deckhouses lower the flow boundary, as indicated by line (*c*).

*(b) Yawed Winds*

With the conventional funnel with raked top, the effect of an angle of yaw limited to 10 deg. is shown in Fig. 5B, as compared with Fig. 5A. The main volume of the smoke is confined within the region marked "Apparent Main Plume," but a perceptible amount of the efflux breaks away and diffuses over the forward edge of the funnel—quite irrespective of the position of the uptake within the funnel casing—and ultimately follows the course between the main plume and the dotted boundary.

If the rake is removed, so that the funnel has a flat top, conditions are greatly improved, as shown in Fig. 5C. The flow lines are here drawn for the design of funnel in which the uptakes do not occupy the whole of the funnel space. Again the diffused smoke boundaries are shown dotted.

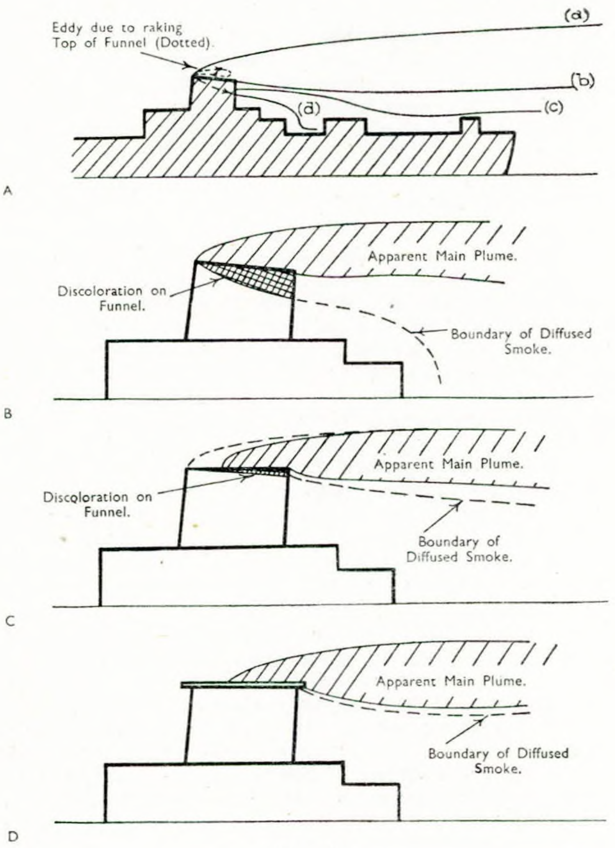

FIG. 5

The addition of a flat plate in the form of a collar around the funnel top ensures that the point of break-away remains at the top of the funnel, and very little smoke diffuses over the edge of the funnel, as shown in Fig. 5D, provided that the yaw does not exceed about 10 deg.

When the angle of yaw is greater than about 10 deg., its effect can become very large. Experiments show that the worst conditions occur when the angle of yaw is between 20 deg. and 30 deg. At these angles, the suction in the lee of the average streamlined casing is very high—probably at least as great as that behind a cylindrical casing—and it acts over an extended area. In these conditions, although the main plume appears to take a path clear of the ship, a considerable volume of loose smoke spills over below the main plume and descends vertically into the low-pressure region in the lee of the funnel, reducing the effective height of the latter very considerably. This loose smoke afterwards disperses down the lee side of the ship and pollutes those parts of the deck and superstructure that lie in its path.

It follows from the foregoing that in winds inclined by more than about 10 deg. a streamlined funnel is in fact no longer streamlined. Hence ships will very often be operating in wind conditions in which the great improvement achieved by streamlining in head winds is not maintained. Consequently the aerodynamic argument in favour of streamlined casings loses much of its force:* it is probable that on many, if not most, occasions a cylindrical casing of the least diameter necessary to deal adequately with the flue gases would be better.

### Methods of Prevention

As we have seen, the primary object in any design should be to eject the smoke well above the turbulence boundary. If this can be achieved, there is unlikely to be any trouble from smoke on deck whatever the strength or the direction of the wind. The most effective methods of preventing the smoke nuisance are therefore those based on this consideration.

#### (*a*) *Height and Shape of Funnel*

The simplest method of ejecting smoke above the turbulence boundary is obviously to make the funnel high enough. The minimum height necessary will be the height of the turbulence boundary, plus the distance by which the suction due to the flow of air past the funnel draws the smoke down below the top. In all except head winds and winds within a few degrees of the ahead (or astern) direction, this distance will be least for a cylindrical funnel of the minimum diameter necessary to deal adequately with the boiler gases. We are therefore led to the conclusion that a return to the tall, narrow, cylindrical funnel offers the cheapest and the most effective cure. If, nevertheless, streamlined funnels are retained for reasons of appearance, the length/breadth ratio of their cross-sections should be as low as possible, their tops should be horizontal rather than raked, and if an annular collar around the top can be tolerated some improvement is to be expected from it.

Improvement may also often be obtained by lengthening a funnel by less than the full amount shown by tests to be desirable for the worst conditions. Thus in a number of warships tested for the Admiralty, increases in funnel height by about 1 to 1½ mean diameters were found to be sufficient. It is not possible, however, to give any general indication of the minimum increase in height that will suffice: if the designer wishes to be certain that any particular ship will be free from smoke trouble, his safest course will always be to have a model tested.

#### (*b*) *Efflux Velocity of the Funnel Gases*

Apart from increasing the funnel height, the method that offers the most promise—although at the expense of some extra power—is to increase the efflux velocity of the funnel gases, either by reducing the exit area of the uptake or by blowing additional air out of the funnel. As already stated, the effect of increasing the efflux velocity usually becomes noticeable when the value of the ratio $s/v$ is between 1 and 2. This enables us to form some estimate of the order of funnel uptake velocity that will be required in practice. For example, if we consider a ship steaming at 20 knots into a head wind of 20 knots, the efflux velocity required for $s/v = 1$ is about 4,000 ft. per minute, and for $s/v = 2$ about 8,000 ft. per minute. If the volume of the funnel gases is 30,000 cu. ft. per minute, and their temperature about 350° F., the values of the horse-power lost in the efflux corresponding to these velocities are 3 and 12, and the values of the extra fan head required are 0·6 and 2·6 in. of water.

These figures for the power lost in the exhaust and the increased duty required of the fans are quite small percentages of the total demands of the ship, which have in any case to be provided; and in view of the valuable improvements they effect in the smoke problem it appears well worth providing for them in the design stage.

An example recently occurred in which effective use was made of both increased height and increased gas velocity, with a very considerable improvement in conditions at small cost. Fig. 6 shows the smoke trail observed on the model ship in the wind tunnel at wind ahead. It will be seen that the trail sweeps a considerable portion of the deck, which was confirmed by full-scale observation on the ship itself. As a result of the wind-tunnel experiments, the diameter of the uptake was halved by fitting a reducing cone with a total angle of rather less than 20 deg. The cone projected about 9 ft. above the funnel top, and the velocity of the funnel gases at efflux was about 6,000 ft. per minute at full power (8,000 H.P.). The corresponding speed of the ship was 17½ knots, so that in a 20-knot head wind the value of $s/v$ was 1·6. With this modification, it was reported that no smoke trouble was experienced. Figs. 7 and 8 show photographs taken on the ship at sea; for Fig. 7 smoke was specially made, and when Fig. 8 was taken tubes were being blown. The improvement compared with Fig. 6 is very marked; and it was achieved at a cost of just over 6 H.P. extra in the discharged gases and an extra 1½ in. of fan head.

The use of a projecting cone, as in this case, does not only increase the funnel height and the efflux velocity; it has the additional advantage that, since it is considerably smaller than the funnel casing, the suction behind it is less and more localized. Hence the effective height of the funnel is increased by more than the added height of the cone.

So far, it has been assumed that the momentum in the funnel gases is increased by increasing their velocity only, not by providing additional air and so increasing their mass as well. This means that when the ship is operating at reduced power the velocity of the gases will be reduced, since less fuel is being consumed and less air is required for combustion. In the ship just mentioned, the values of $s/v$ in a 20-knot wind at 16½ knots (full speed), 15 knots and 13½ knots are respectively about 1·6, 1·4 and 1·0. The relative wind over this range only falls from 36½ to 33½ knots. From this it is clear that if only the combustion air is used, although it may be speeded up sufficiently at full power by reducing the uptake diameter, conditions will not be so good at lower powers. A variable outlet area would overcome this difficulty, but probably only at the expense of other difficulties of a different kind. A better course appears to be to supply extra air. It is important to notice that this extra air need not pass through the boilers, and also that, provided the fans are able to produce a high enough value of $s$ at full power, no extra fans or higher duty for existing fans will be required to maintain the requisite value of $s/v$ at lower powers. Briefly, all that is needed is to run the fans at full capacity whenever the natural wind conditions demand it; only the air needed for combustion need be passed through the boiler, the air trunking being arranged to bypass the remaining air direct to the uptake. This possibility was first mentioned by Mr. Burge, who discusses it in greater detail in Part II of this paper.

An alternative way of using extra air is to inject it in the form of a high-velocity sheath or annulus surrounding the natural funnel gases. Nolan discussed this possibility in his paper and said that it was "very effective. . . . The annulus acts as an ejector and also an isolating belt which helps to prevent the stack gases from being drawn into the (low-pressure) zone immediately behind the stack." The effectiveness of this high-velocity sheath is shown by the photographs of Fig. 9, which were taken at the National Physical Laboratory. A marked improvement in the path of the smoke trail is produced even with a funnel of *reduced* height and with the low $s/v$ ratio of ½.

So far all the experimental data on this device have been obtained on the model scale, and their practical implications are discussed by Mr. Burge in Part II. The correlation between model and full scale has yet to be established.

#### (*c*) *New Shape of Funnel*

In May 1948, an interesting new development was described in a paper read by Valensi and Guillonde[3] to the Association Technique Maritime et Aéronautique. This takes the form

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* It is assumed that a swivelling streamlined casing is impracticable.

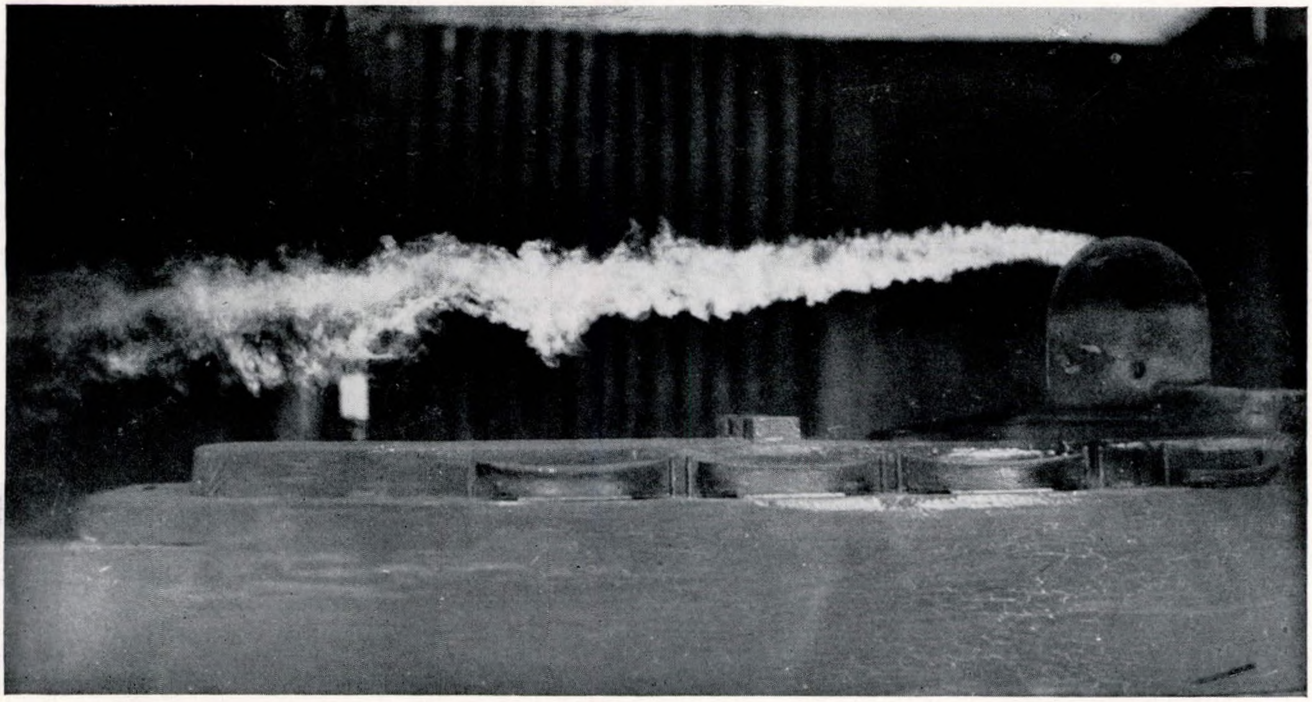

FIG. 10

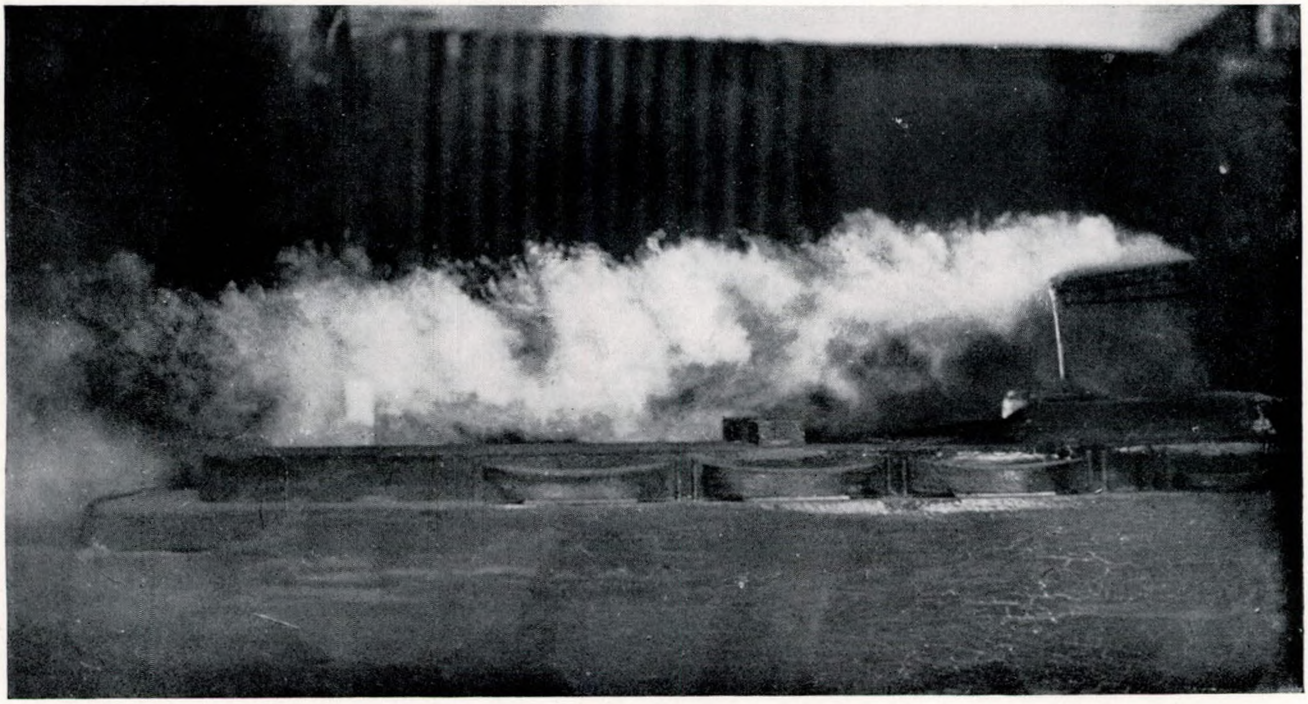

FIG. 11

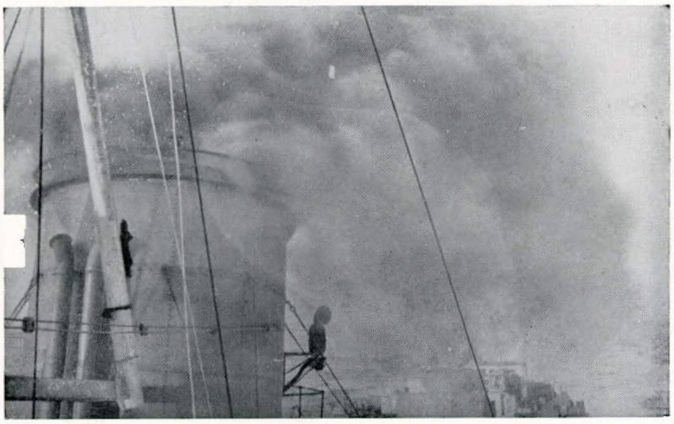

FIG. 12

FIG. 13

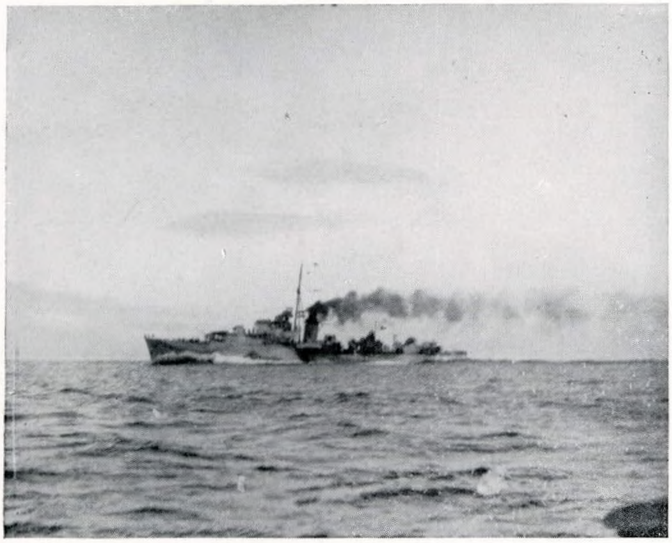

FIG. 14

of a funnel whose cross-section is shaped like that of a symmetrical aerofoil with maximum thickness 20 per cent of the chord. In side elevation, the funnel resembles a short half-wing of an aeroplane, with a rounded tip forming the funnel top (see Fig. 10). The smoke emerges in the locality from which the trailing wing-tip vortex springs, and is carried downstream by this vortex, one of the chief characteristics of which is that it preserves its individuality for a considerable distance downstream. The authors of the paper state that they developed this device in wind-tunnel experiments and confirmed its effectiveness in full-scale tests at sea. In the particular case that they examined they found that, provided the funnel was of sufficient height just to penetrate the turbulence boundary, the smoke was carried well clear of the deck at all inclinations of the relative wind from dead ahead to 30 deg. on the bow. A typical condition is shown in Fig. 10, which shows their model in the wind tunnel in a 10 deg. wind. Fig. 11 shows the same model with a conventional funnel; the great improvement is evident. The paper itself includes other photographs taken in the wind tunnel at zero yaw. Again the improvement is pronounced, and it is confirmed by a photograph of the full-scale vessel taken at sea.

From the information given in the paper, this device, which is the subject of French Patent No. 537822 of 12th July, 1947, seems to be one of considerable promise. Further verification of its effectiveness appears desirable, particularly since, so far, it appears from the paper to have been tried only in one particular ship. Its behaviour in following winds also needs examination.

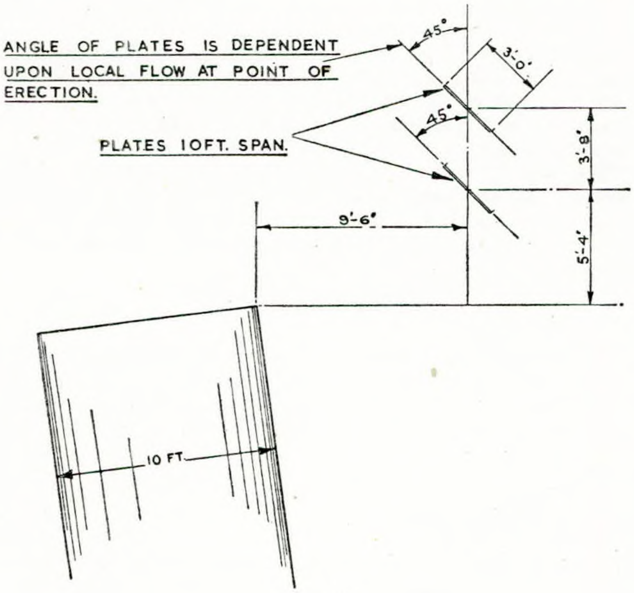

FIG. 15

### (*d*) *Deflector Plates*

Experiments made for the Admiralty have shown that inverted aerofoils placed ahead of the funnel top and at suitable angles of incidence (see Fig. 13) can produce a powerful up-draught at the top of the funnel, which will carry the smoke well above the turbulence boundary. Similar effects can be obtained with flat plates; but in either case the deflectors will probably have to be at a height at least equal to that of the turbulence boundary, and are unlikely to be effective if the funnel top is much below it. Further, the deflectors must be fairly large—of span about equal to the funnel width and chord about one-third or one-quarter of this width—and strongly mounted, since the wind forces on them may be substantial. This need for size and strength may be a disadvantage.

There is, however, no doubt that the device is effective. Fig. 12 is a photograph of the smoke from the funnel of a destroyer, showing the after armament enveloped in smoke. Figs. 13 and 14 show how the smoke is lifted by a pair of aerofoils at 45 deg. incidence, and how the trail keeps well clear of the deck. All the photographs relate to a ship speed of 20 knots and a relative wind of 42 knots. Fig. 15 is a sketch of the dimensions and the relative positions of the funnel top of the same vessel, and of a pair of flat-plate deflectors designed on the basis of the results with aerofoils depicted in Figs. 13 and 14.

The deflector plates must be upstream of the funnel; hence an additional pair will be necessary for following winds, unless the pair used for head winds is mounted on a movable support. Adjustments of the deflectors, or additional deflectors, will also be required for winds yawed by more than 5 deg. or so.

### (*e*) *Cowls and Hoods*

A cowl or a hood on the top of a funnel sometimes effects an improvement. One of the main uses of such devices is to improve local conditions; a typical example is that of a bridge situated fairly near the funnel top, where trouble may be experienced from smoke in a following wind. Two classes of naval vessels in which this occurred were reported to be improved by funnel cowls, but in each case the funnel height was also increased. In any event, fitting a cowl to the top of an existing funnel in itself obviously increases the effective height, so that some of the improvement must be due to this cause as well. Some may also be due to the fact that a cowl generally rounds off the top of the casing and eliminates the sharp forward edge.

Devices of this kind do not lift the smoke as do some of the more effective expedients already mentioned; they merely direct it away from the region which is to be kept clear. It is probable that their usefulness is restricted to special cases such as that mentioned above. In winds off the bow they are better than conventional funnels in that the smoke is emitted in a region further away from the leeward suction and so is less likely to be drawn down. On the other hand, backward-facing cowls remove all or most of the vertical velocity from the smoke before emission, and are subject to obvious disadvantages in following winds.

To reduce extra loads on the fans, cowls should be so designed that any change in the direction of flow of the gases from vertical to horizontal occurs as gradually as possible.

### (*f*) *Miscellaneous Devices*

During the past few years a number of aerodynamic devices have been introduced by different designers. In general, we can say of such devices that, if they are to be effective, they must either divert the main flow, or else expel the smoke from the funnel at a velocity high enough to ensure penetration to a height above that part of the flow which descends to deck level. In either case they must use the energy of the wind, and therefore they are unlikely to be effective if they offer appreciable resistance to the free flow. For this reason, little success has attended devices based upon the hope that the air flowing past the funnel will enter slots or ducts in the front of the casing, and not only change its direction but also increase its velocity in the process. Unless the slots have a very large inlet area, and unless the flow paths inside the casing are made to have low resistance, most of the free air meeting the funnel will take the path of lower resistance around the outside, and no significant amount will enter through the slots. Neither will slots cut in the rear of the casing improve the general path of the lower fringes of the flow boundary because, as shown in Fig. 5B, the break-away at the top of the funnel occurs well forward.

Some of the modifications that have been introduced from time to time raise the point of emission above that from the original funnel. They are therefore equivalent to an increase in the height of the funnel; and if they produce any improvement at all, it is probably due mostly, if not entirely, to this increase in height and not to the modifications themselves. Moreover, even if there is some improvements at wind ahead, it does not follow that there will be any in a yawed wind, in which conditions are more stringent.

### Soot and Ash

As already remarked, if comparatively large particles of soot and ash are emitted from the funnel, they will inevitably fall on to the deck if the speed of the relative wind is not great enough to carry them clear of the ship before their natural velocity of fall brings them down to deck level. This trouble is therefore most prevalent in harbour, in light winds and at slow operating speeds, or in following winds. The only possible remedies are to prevent the formation of these large particles as far as possible by constant attention to the combustion control, or to remove them before the smoke leaves the uptake by means of devices such as vortex soot extractors. It is a matter for the shipowner to decide between the nuisance of soot and ash contamination on the one hand and the initial cost and maintenance expense of soot extractors and combustion control on the other. It is, however, worth bearing in mind that speeding up the funnel gases, as advocated earlier in this paper for keeping the decks clear of gases and fine smoke, will help towards reducing trouble due to the coarser particles, because the particles will have further to fall and hence a better chance of being swept clear of the ship by whatever wind there is.

The coarse particles are also liable to be troublesome when boiler tubes are blown, but judicious adjustment of speed and course during the process, in relation to the strength and direction of the wind, can improve conditions considerably. The object should be either to get a high value of $s/v$, a sufficiently high value of $v$ to carry the particles away, and a wind inclination of not more than 10 deg. ahead or astern; or a high value of $s/v$, a sufficiently high value of $v$, and a wind inclination of between 45 deg. and 90 deg., so that as much as possible of the soot is taken over the side. If the first alternative is adopted, the ship's speed will generally have to be reduced in a head wind to increase $s/v$, and may sometimes with advantage be increased in a following wind to get a sufficiently high $v$.

## Part II

### EXPERIMENTAL TECHNIQUE

By C. H. Burge

The direct purpose of wind-tunnel experiments on model ships is to facilitate the study of the flow pattern of funnel gases, firstly in relation to the estimated conditions of normal operation pertinent to the ship, and secondly to devise means of diverting the flow boundaries which descend to deck level within the dimensions of the ship. Various methods have been employed in attempting to raise the lower boundaries of the smoke plume clear of the decks and superstructure. Most of these have proved abortive, because they are only effective over a limited range of wind variation and, without the aid of power, they are unable to assist the dispersal of funnel gases. There is no empirical law which will enable the shipbuilder to arrive at the efficacy of a funnel auxiliary and he must of necessity have recourse to the method of trial and error. It follows therefore that, provided the results of model experiments may be relied upon, the wind tunnel is a more economical method of studying smoke conditions than direct full-scale investigation.

In the field of marine engineering, the wind tunnel is an unusual piece of research equipment, and the shipbuilder might, at first glance, have some misgivings in accepting the photographic records of the flow patterns given by the model, since they have the general appearance of being much better defined than those experienced full-scale. This apparent difference between the two sets of conditions is explained by the fact that the wind speed over the model is maintained at a constant value and the resultant smoke plume maintains a definite pattern according to the ratio of the speed of the funnel gases to that of the wind over the ship. On the other hand, the wind over the ship at sea is inconstant in velocity, so that the ratio to the speed of the funnel gases is also constantly changing and the pattern of the smoke plume changes accordingly.

The full-scale plume recorded by the eye is similar, in effect, to a series of instantaneous exposures; but in model experiment it would not be practical to define the plume boundaries by a sequence of instantaneous exposures, and therefore a time exposure is employed, usually of about 30 sec. duration. This record may be considered an integration of the sequence of instantaneous exposures over that period, and those wisps of smoke which occasionally break away from the apparent main plume actually define the boundaries of the diffused smoke. This diffused smoke is not as heavily laden with soot particles as the main body of the effluent, but over a period of time it will deposit a coating of soot on all structures within its path. The experimenter therefore assesses his success by the extent to which he has diverted this smoke from the decks and superstructure of the model.

In the course of the model experiments the comparison of several modifications may be required, and it is convenient to use the same velocity ratio at all angles of wind between 0 deg. and 30 deg., this being the usual range of the investigation. In the assessment of the final results, however, allowance must be made for the reduction in the speed of the relative wind as the ship turns across the natural wind.

### Experimental Apparatus

*The Wind Tunnel*

A longitudinal section of the wind tunnel used at the N.P.L. for experiments on model ships is given in Fig. 16.

The wind tunnel is an apparatus for generating a steady, uniform current of air, in which details of the flow past

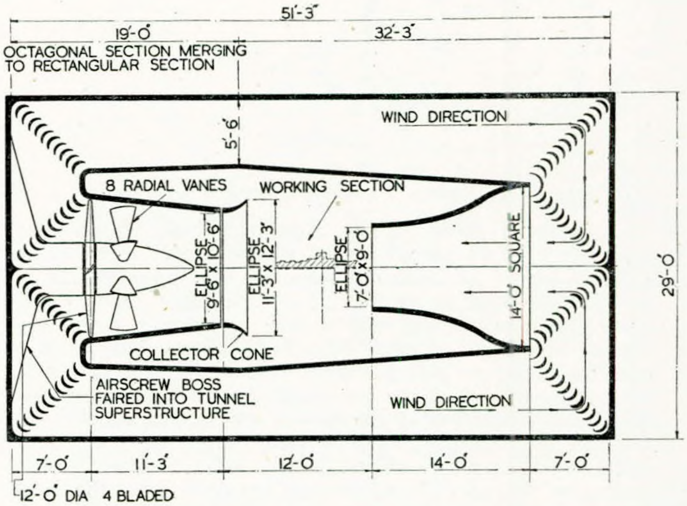

FIG. 16.—VERTICAL SECTION OF N.P.L. OPEN JET TYPE WIND TUNNEL

stationary models may be investigated, or, when necessary, the forces and pressures due to the flow can be measured. Fundamentally, the principles of wind-tunnel research as applied to investigations of the air flow over ships are simple, the flow being examined generally by means of smoke introduced at suitable places. Considerable care, however, must be taken if the results of the model experiments are to represent what actually happens on the full-scale ship. Without these precautions incorrect inferences can easily be drawn from the model results. The cross-section of the airstream at the working section must be large enough to enable a model of reasonable size to be accommodated without serious disturbance of the flow, the velocity distribution across the working section must be uniform, the airstream must be steady, and all large eddies and disturbances must be removed before the air reaches the working section. In order to achieve these and other necessary conditions much care has to be taken in the design of the wind tunnel; and any attempt to get results with crude, simple apparatus is strongly to be deprecated.

### *The Model*

The dimensional limitations of the wind tunnels restrict the overall length of the model to 8 ft., and the scale of the model, therefore, must be selected to suit that dimension. The method of construction is not important, nor is it necessary to reproduce the components and fittings in minute detail, but all obstructions and excrescences likely to have an influence on the flow of air over the model must be included. In general it is sufficient to represent them in block form to their overall dimensions.

The model is positioned in the wind tunnel on an 8-ft. diameter turntable rebated into a platform supported in the central horizontal plane of the working portion. Below the turntable the delivery pipes to the model funnels are each taken to separate fans and all to a common smoke supply. A diagrammatic sketch of the arrangement is given in Fig. 17. The flanged couplings connecting the sections of the delivery system immediately beneath the model are designed with sleeves to fit pipes of different diameters between $\frac{3}{4}$-in. dia. and $1\frac{1}{4}$-in. dia. Each flange is recessed to accommodate interchangeable orifice plates of different diameters, and, to ensure an airtight joint at the orifice and an unbroken surface in the wall of the pipes after assembly, the whole unit is precision machined.

The confined space beneath the platform renders it impracticable to provide a separate hot air supply to the delivery fans, and therefore it is frequently difficult to prevent the injected smoke from condensing on the surfaces of the orifice plates, with the consequent blocking of the pressure tubes. To reduce the susceptibility to blockage, the tubes are displaced one pipe diameter from the plane of the orifice, and the delivery pipes on both sides of the orifice are heated electrically and lagged externally against cooling. Care must be taken in controlling the applied heat, because perception of the flow boundaries at the point of emission is lost if the effluent is overheated. This is particularly so when steam is used as the agent for visualization. The pressure difference at the orifice is measured on a manometer from which the velocity of efflux may be determined in terms of the quantity flowing through the orifice as given by the usual relationship:

$$Q = C A_2 g \sqrt{2 \rho \left(\frac{p_1 - p_2}{1 - m}\right)} \quad . \quad . \quad . \quad . \quad (1)$$

where $m = \frac{A_2}{A_1} = \frac{\text{area of the orifice}}{\text{area of the pipe}}$,

$\rho$ = density of the fluid,

$p_1 - p_2$ = pressure difference at the orifice.

The coefficient of discharge $C$ is dependent upon (*a*) the velocity distribution across the pipe, (*b*) the ratio of the diameter of the orifice to that of the pipe, and (*c*) the disposition of the pressure points upstream and downstream of the orifice.[4, 5]

When an effluent containing moist gases is discharged, it is an advantage to displace the pressure tubes from the plane of the orifice to avoid blockage of the tubes by condensation. As conditions differ from standard it becomes necessary to obtain the value of $C$ by calibrating the orifice meter against a standard flowmeter or, if the model funnel is large enough, to explore it by pitot-static traverse. In either method it is convenient to record the results in terms of the efflux velocity and the pressure difference $p_1 - p_2$.

A change of flow occurs at low speeds and it is preferable to record the low-speed calibration separately from the higher values. In general, a discharge of 6 cu. ft./min. to 25 cu. ft./min. from a 2-in. diameter delivery pipe is adequate for most experiments on model funnels.

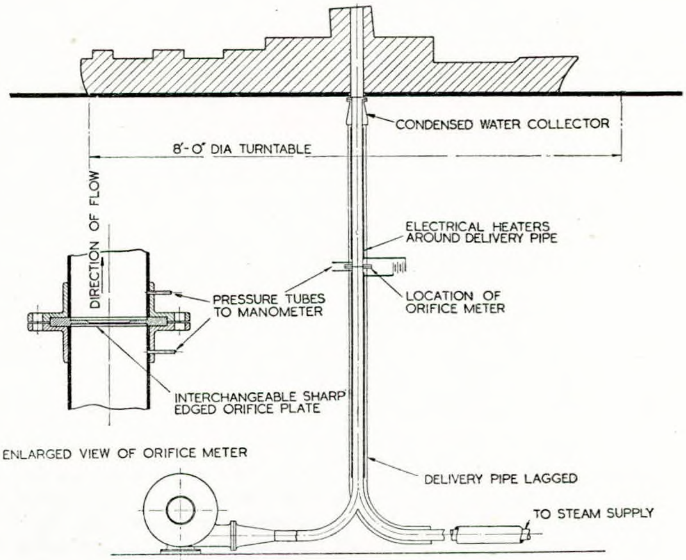

FIG. 17.—DIAGRAMMATIC SKETCH OF "SMOKE" SUPPLY TO MODEL FUNNEL

Although we refer to the descent of funnel gases in terms of the ratio of the velocities of efflux and relative wind, the actual problem is linked with the momentum of those quantities. It is fortunate, therefore, that the pressure difference at the orifice actually gives momentum quantities and thereby obviates the necessity of determining the density of the fluid passing through the delivery pipe.

From the relationship given in (1) it is apparent that, since $A_2$ is constant in any one test, the quantity $Q$ is proportional to $\sqrt{\rho(p_1 - p_2)}$

or $$Q^2 \propto \rho\,(p_1 - p_2);$$

i.e. $$\begin{aligned} p_1 - p_2 &\propto \frac{Q^2}{\rho} \\ &\propto \frac{Q}{\rho} \times \rho V A \\ &\propto Q V A \\ &\propto \text{momentum} \times A \end{aligned}$$

To produce a visible discharge from the model funnel, either steam or atomized paraffin is injected into the delivery system at a point below the orifice meter. The choice depends chiefly upon the scale of the model, for if the diameter of the model uptake is less than $\frac{7}{8}$-in. diameter the condensation from the steam will prove a nuisance, since it will drain back along the uptake wall and obstruct the pressure tubes.

With larger model funnels most of the condensation takes place in the exposed portion of the funnel above decks, and it is usual to incorporate a receiver between the funnel and the delivery system to drain off the water produced by condensation.

In the alternative method where atomized paraffin is employed the condensation is appreciably less. If the smoke is over-cooled, liquid paraffin will accumulate at the funnel exit and some form of drain beneath the model funnel must be fitted to provide against this contingency.

A schematic diagram of an atomizer is given in Fig. 18 (see also reference 6). Commercial paraffin is contained in the reservoir, which is adjustable in height to vary the head of liquid delivered to the jets. From the reservoir the paraffin passes through a filter to the heater, and on the remote side of the heater the paraffin, now in the form of smoke, enters the mixing chamber via an array of jets. Air to the mixing chamber is supplied by a fan, which carries an auxiliary valve to regulate the amount of air entering the mixing chamber. By this means the density of the ultimate smoke cloud may be controlled such that, in still air, the smoke remains in suspension. The air pipes to the mixing chamber are arranged to blow directly across the jets to produce "atomization." The mixture then passes through a cooler to a valve, which, in conjunction with the speed control on the fan, adjusts the quantity delivered to the model. The intensity of the smoke is adjusted by varying the current supplied to the heater, an excessive heat produces a very thin smoke, whilst insufficient heat results in excessive condensation on the funnel wall.

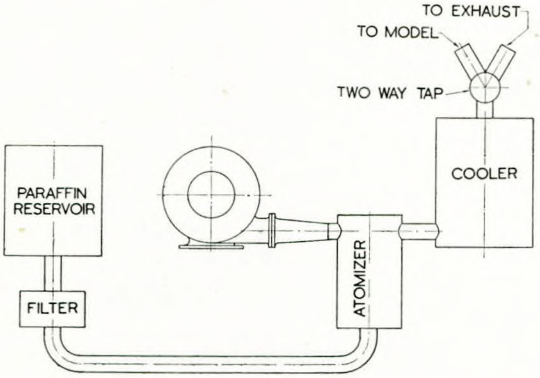

FIG. 18.—SCHEMATIC DIAGRAM OF PARAFFIN SMOKE GENERATOR

### Determining the Extent of Deck Contamination

The point of interest in the photographic records of a steam or smoke plume lies chiefly in the definition of the diffused lower boundary, in relation to its height over the deck corresponding to modifications of the ratio $s/v$. To study the concentration of the smoke at deck level it is necessary to employ a method which gives a direct indication of those parts of the deck actually contacted by the descending funnel gases. This is best achieved by a chemical reaction method. The technique which has proved satisfactory at the National Physical Laboratory requires the model to be sprayed with a white paint containing lead acetate* and a reagent introduced into the effluent.

Air only is discharged as the effluent, and after the velocity conditions have been adjusted to the required velocity ratio, sulphuretted hydrogen is injected slowly into the delivery pipe until the concentration over the deck is adequately defined by the resulting black stain. The result must be noted without undue delay, because the chemical reaction will continue after the experiment is completed and parts of the model beyond the boundaries of the funnel gases may be affected also and produce a misleading impression of the extent of the concentration. The model must be cleaned and re-sprayed with the paint for each record.

### The Effect of Buoyancy

Another method of tracing the plume boundaries is to project the flow from the funnel on to a screen in the form of a shadowgraph and to sketch in the flow boundaries by hand. Because of the difficulties experienced in satisfying the similarity conditions with this technique, it has been found necessary to restrict these experiments to the detailed study of the buoyancy effects due to temperature as related to an unobstructed model of a funnel or chimney only. Increments in the height of the flow boundaries due to buoyancy are approximately in direct proportion to the difference between the free stream temperature and the funnel gas temperature, and also to the linear dimensions of the funnel uptake, but they are inversely proportional to the square of the relative wind velocity. Therefore, to represent the modification to the flow boundaries due to variations in temperature on a wind-tunnel model of the order of $\frac{1}{8}$ in. to 1 ft. scale, the velocity conditions relative to normal cruising speeds would be of the order of 2 or 3 ft. per second. The difficulties of maintaining a uniform velocity distribution across the working section of the wind tunnel and within the model uptake are obvious, but, nevertheless, the mean values from a series of observations, for a particular set of conditions, give remarkably good agreement.

In this technique no visualizing agent is injected into the effluent. Air is taken from the reservoir of a compressor and fed through a low-capacity gas meter to the delivery system of the model (Fig. 19). The first section of the pipeline carries two 1-kilowatt heaters within the pipe, which heat the central core of the column of air passing along the pipe. The heated air then passes into a section of the pipe with a heating coil wrapped around it and extended as close to the point of emission as the model will allow. The heating stages thus separated provide a far better control of the temperature distribution across the pipe than would be possible with the heating elements located over the same section of the pipe. To minimize heat loss the whole of the delivery system is lagged to a point as close to the funnel exit as aerodynamic considerations will tolerate.

The temperature at any point of interest is measured in the normal manner by a copper-constantan thermocouple. At the funnel exit one thermocouple is attached to the wall of the uptake and another, with a sufficient length of lead to avoid wall-temperature interference, is positioned at the centre of the uptake. The cold junctions of both thermocouples are positioned in the unobstructed free wind stream. The isothermals for a given velocity ratio and temperature difference, measured by a thermocouple exploration of the plume, are given in Fig. 20.

A number of experiments on model factory chimneys have been conducted with this type of apparatus, and from the results the mathematical deductions relative to the prediction of the flow boundaries from a factory chimney discharging into a turbulent air stream have been analysed by Mr. L. W. Bryant, and reduced to coefficients in terms of the linear dimensions of the chimney and the velocity ratio $s/v$ (see also reference 7).

As it is unlikely that ships' funnels will at any time be built high enough to be beyond the aerodynamic interference of obstructions on board the ship, the analysis from the heat experiments cannot be applied directly to the design of ships' funnels in general. Nevertheless, it is of value to the designer to be informed of the effects of temperature on the behaviour of a column of smoke discharged into an air stream normal to its path. As the smoke impinges on the streamlines passing the funnel outlet, the familiar billowing vortices are set up by the aerodynamic forces acting on the smoke jet, and, as the plume diverges from the point of emission, the vortices progressively entrain an increasing amount of the surrounding colder air. The funnel gases therefore rapidly lose heat, but the height gained by buoyancy from the initial heat in the plume is reflected over the whole course of the plume and the lower fringes of the flow boundary would remain at a greater height above the deck than those of a

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* For formula see Appendix.

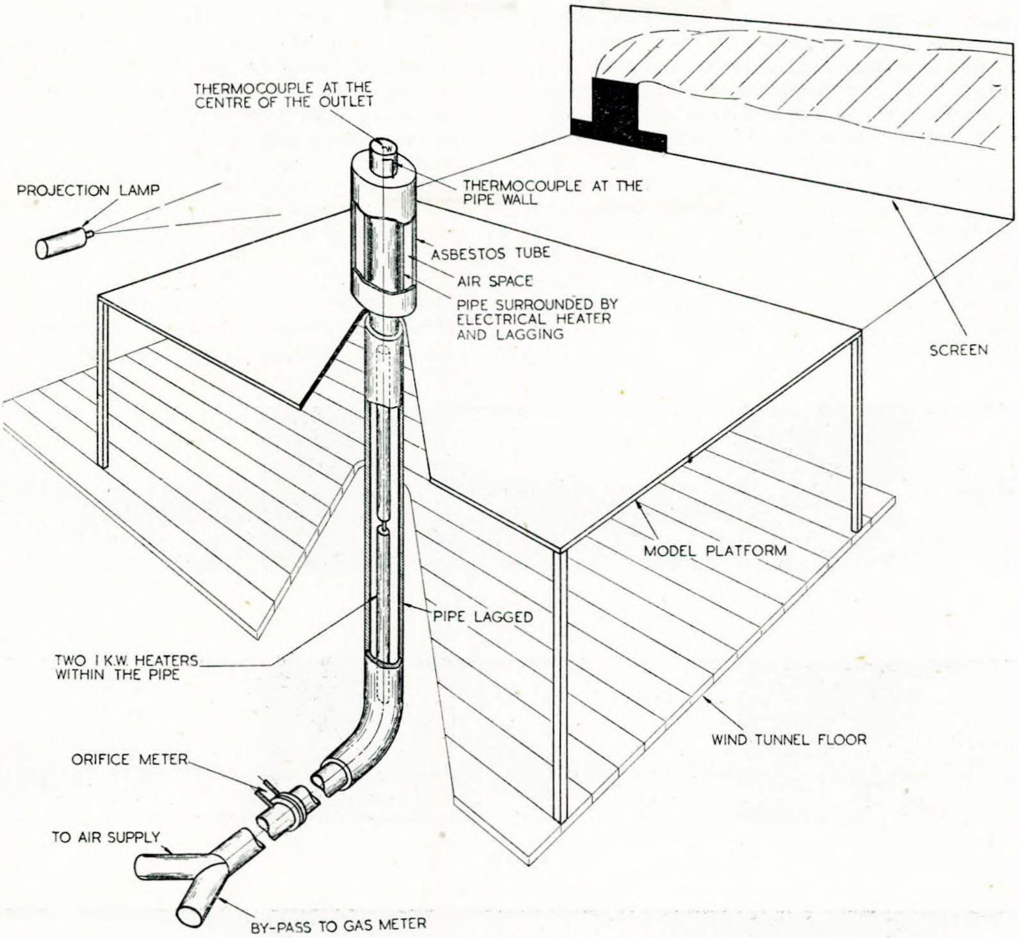


FIG. 19.—APPARATUS FOR EXPERIMENTS ON A HEATED JET

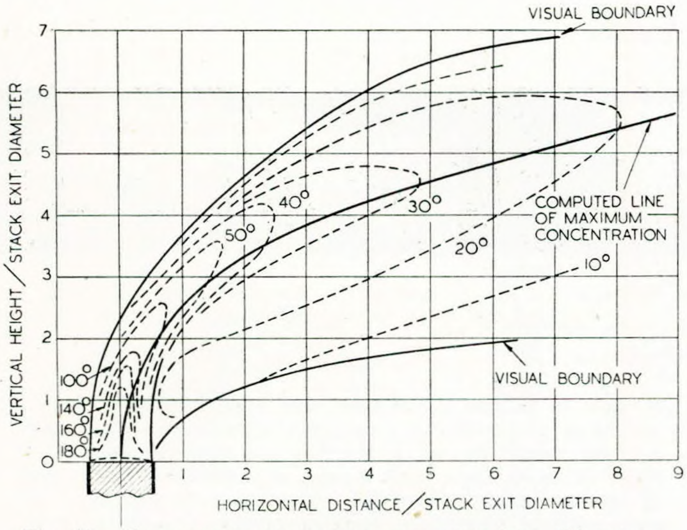


FIG. 20.—CONTOURS OF CONSTANT TEMPERATURE (DEG. C.) FROM A THERMOCOUPLE TRAVERSE IN THE PLANE OF SYMMETRY OF A MODEL SMOKE JET

Efflux velocity/wind velocity = 2/1.
Temperature difference at exit = 200 deg. C.

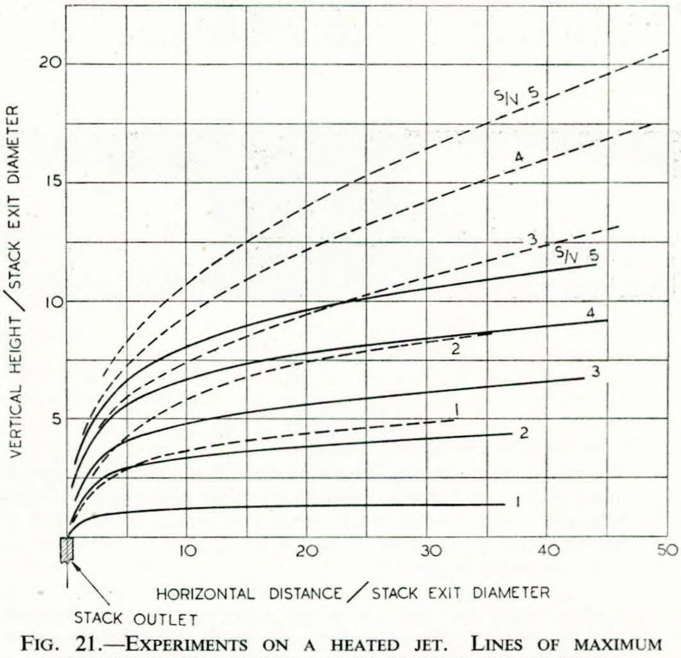
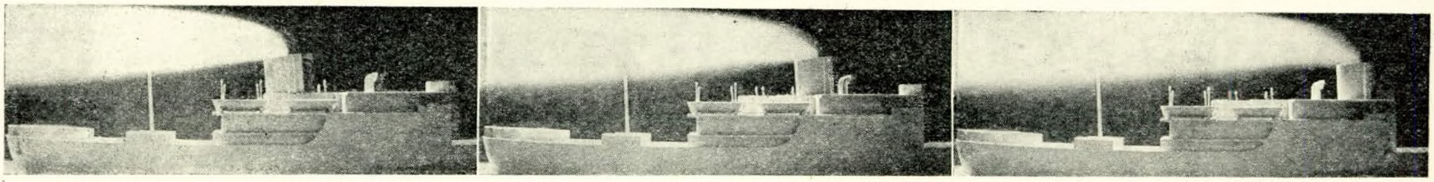


FIG. 21.—EXPERIMENTS ON A HEATED JET. LINES OF MAXIMUM CONCENTRATION OF SMOKE FROM CIRCULAR MODEL STACK

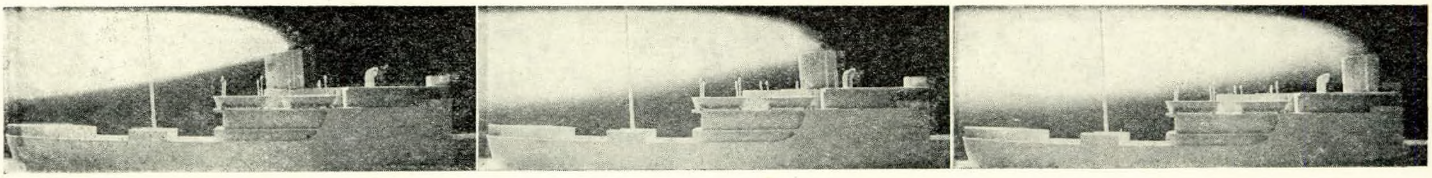
Temperature difference 180 deg. C.
Heated effluent shown dotted.

similar cold plume. Nevertheless, it is important to bear in mind that a heated jet has a lower density than a cold jet, and therefore it has less momentum, so that it would be depressed to a lower level at a similar velocity ratio. Consequently, for a given boiler discharge, part of the advantage gained from the increased velocity of the heated effluent is counterbalanced by the loss of momentum.

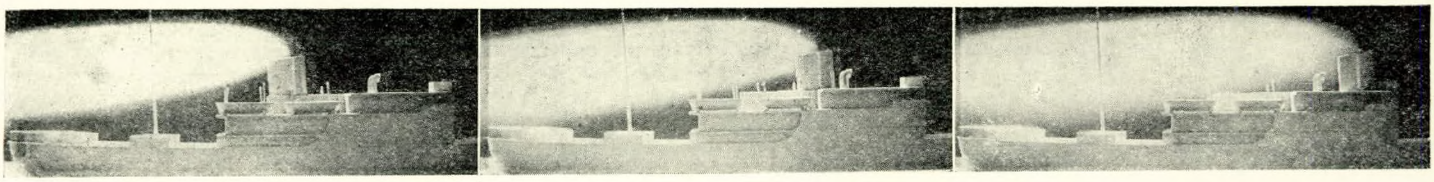
From the series of curves, Fig. 21, it may be seen that it is an advantage to maintain as high an efflux velocity as possible, because there is a greater gain from buoyancy at the higher values of $s/v$. The values of $s/v$ above 2/1 are applicable chiefly to instances of following winds and harbour conditions; when the ship is heading into wind it should be unnecessary for a well-designed funnel to discharge the gases at a higher velocity ratio than 2/1.



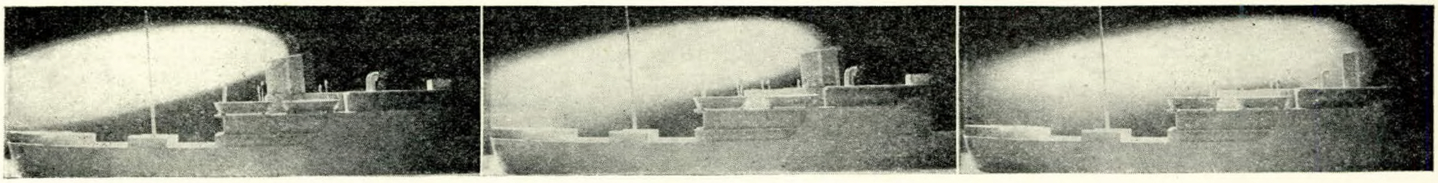
Wind ahead



Wind 10 deg. starboard



Wind 20 deg. starboard



Wind 30 deg. starboard

FIG. 22.—THE EFFECT OF FUNNEL POSITION
Efflux velocity/relative wind velocity = 2/1.

*Positioning the Funnel*

Mention has already been made of the importance of raising the funnel above the disturbances produced by bluff obstacles upwind of it, and, from this point of view, it is obvious that the position of the funnel relative to the obstacle is a design fundamental.

If, for example, we take an average funnel typical of a passenger liner and apply it to the superstructure in different positions, we shall see from the photographs reproduced in Fig. 22 that the descent of the funnel gases is greater when the funnel is close to the frontal face of the superstructure than when it is in the aftermost position. Also, in winds off the bow, the flow pattern from the funnel in the forward position is appreciably more disturbed than when the funnel is partially screened by the breakaway from the superstructure. In following winds the conditions would be reversed, except those of velocity ratio which would improve with increasing ship speed.

However, both aesthetic considerations and practical requirements of the boiler-room arrangements are factors of importance, and either might outweigh the aerodynamic advantages of a differently positioned funnel.

*Position of the Uptake within the Funnel*

The flow boundaries for a number of funnel modifications have been sketched in the first part of this paper (Fig. 5). It must be accepted, however, that objections to a slavish adherence to aerodynamic efficiency must prevail when such a funnel would be out of keeping with the general lines of the ship, particularly as it is only at wind ahead and small deviations therefrom that the improvement is achieved. In circumstances where the designer prefers a slight rake to improve the appearance of the funnel the problem arises, where within the funnel casing shall the uptake be arranged? Frequently the position will be decided by the dimensional limitations of soot extractors and similar auxiliary equipment within the funnel casing; but, nevertheless, it should still be possible to allow a sufficient length beyond such fittings to lead the uptake to the point where it will be most effective in discharging the gases clear of the funnel wake.

The smoke boundaries and aerodynamic streamlines at wind ahead indicated on the diagrams (Fig. 5) show that the point of breakaway will be at the leading edge of the funnel irrespective of the position of the uptake. Under operational conditions, however, it is very doubtful if the wind is directly ahead for any appreciable part of a voyage, consequently this wind direction becomes of least importance.

Model experiments have shown that the worst conditions prevail when the ship is 20 deg. to 30 deg. out of wind, and, therefore, the shipbuilder should concentrate his efforts to obtain deck clearance over this range. The first step is to get the uptake as far aft as the funnel casing will permit and then to increase the efflux velocity until the lower fringes of the plume are dispersed clear of the disturbances in the immediate wake of the funnel. For any new design the minimum value for the efflux velocity is more easily determined by wind-tunnel experiments; in fact it is desirable that it should be so, because by this means it is possible to arrive at the power factor to be employed in the design of the forced draught and induced draught fans. By this approach to the problem a sufficient reserve of power could be provided to give clear decks at all angles of wind.

It must be appreciated, however, that the wind-tunnel results are expressed in terms of the velocity ratio of efflux to relative wind, and it is for the designer to decide the figure for the speed of the natural wind to which he is prepared to power his fans.

### Methods of Prevention

*The Air Annulus*

Model experiments on the effectiveness of an auxiliary air discharge around the funnel were initiated by the Admiralty in 1938, chiefly with a view to clearing the low-velocity region at the wall of the uptake and thereby preventing wisps of smoke from seeping down the funnel and entering the boiler-room ventilators. These experiments successfully dealt with that special problem, but they were not extended to deal with the main volume of smoke which probably descended to deck level at a more remote distance from the funnel.

The very small annular width which must be used in the model to correspond with full-scale dimensions requires the model funnel to be made to a high order of accuracy. The final portion of the uptake must be precision machined, and the annular spacing at the outlet must not only be concentric, but it must also be designed to give a good velocity distribution around its periphery. It is convenient to design the annular space leading to the outlet to the maximum width anticipated in the experiment, and thereafter to interchange separate nozzles to reduce the size of the annulus. The annular width ultimately decides the scale of the model, for it is not advisable to reduce that dimension below $\frac{1}{8}$ in. If, however, this restriction results in the scale of the model being too large for the particular wind tunnel envisaged for the tests, then it is preferable to divide the experiments into two separate parts. First, a study would be made of the flow boundaries from a larger scale model of the funnel mounted on the superstructure only, and later the funnel arrangement giving the best results would be applied to a smaller scale model of the complete ship, when the whole plume would be recorded. On this model the actual annulus would be omitted and the resultant plume would represent the condition when the efflux velocity and annulus velocity were equal. If the boundaries of the plume are studied over a range of velocity ratios and superimposed on those obtained from the first part of the experiment, the descent of the funnel gases may be estimated for any wind condition within the limits bounded by the experiment.

It is not possible to arrive at an empirical formulae for the design of annular uptakes because the wide variations in ship design result in dissimilar streamlines in the plane of the funnel. The experiments which have so far been completed on this project indicate that the width of the annulus should not be less than 10 per cent of the uptake diameter. The velocity of discharge is dependent upon several factors, the chief of which is that of funnel height, for it is obvious that a high funnel would require a lower discharge velocity than a short funnel. Taking an average of the funnels of modern vessels, the annulus velocity should be between one and a half times and twice the velocity of the relative wind over the ship.

To provide a typical example, we will assume an uptake diameter of 5 ft., which, with a surrounding annulus 10 per cent of the uptake diameter, gives an overall dimension of 6 ft. diameter.

If the cruising speed is 15 knots and the natural wind 20 knots at wind ahead the relative wind speed over the ship will be 35 knots. At velocity ratios of 2/2 and 2/1 the quantity of air discharged from the annulus would be approximately 77,000 cu. ft. per min. and 102,000 cu. ft. per min. respectively.

The energy of the jet at the outlet would be 13·1 H.P. and 31 H.P. respectively, and the fans required to deliver that power would, in addition, have to overcome the drag losses in the trunking.

The full-scale application of the air annulus must be arranged in the initial stages of the funnel design, for it is generally difficult to find adequate space for a separate fan and trunking after the ship is built. Ideally, the fan should be controlled by an anemometer positioned as near as practicable within the undisturbed flow over the ship, so that the annular discharge is operated entirely according to the conditions of the relative wind. Such an anemometer would, of course, respond to small variations in wind speed and direction, but suitable damping could be provided in the fan speed-control system to restrict the fan so that it followed sustained conditions only.

*Throats or Nozzles*

To install an air annulus around the uptake of a ship already in service would probably entail such extensive modification as to render it impracticable or too costly. A more convenient alternative would be that of fitting a throat or nozzle at the uptake outlet to reduce the area at the point of emission and thereby increase the efflux velocity in direct proportion to the areas of the uptake and the nozzle. It is important that the velocity distribution across the outlet should be as uniform as possible and this can only be achieved with an aerodynamically efficient nozzle. Two examples of a suitable nozzle are given in Fig. 23 "A," from which it may be seen that the sides of the nozzle require to be curved. This feature makes construction far more difficult than a straight-sided cone giving a similar contraction ratio, but the very much improved performance warrants the additional

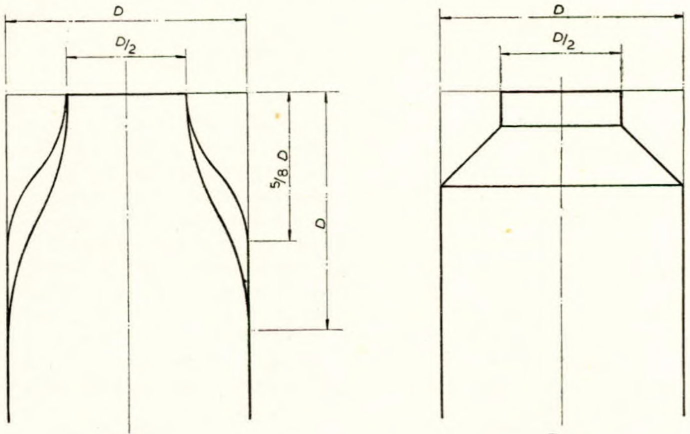


FIG. 23.—NOZZLE PROFILES

labour and expense. It will be appreciated, therefore, that a sharp contraction like that shown in "B," Fig. 23, should be avoided.

It must not be overlooked, however, that without the introduction of extra air into the uptake this device is most effective at full power only; at lower ship speeds the efflux velocity is relatively lower and the consequent plume from the funnel will be depressed closer to the decks.

### *A Proposed Solution to the Problem*

As the results of wind-tunnel experiments have generally indicated the need of high efflux velocities to raise the funnel gases clear of the turbulent wake of the funnel and ship's superstructure, the designer is faced with the decision whether or not the nuisance value of the descending funnel gases is serious enough to warrant the installation of additional equipment to supply the power solely for that purpose. Hitherto the project has always been received very unfavourably, but the fact remains that mechanical power must be employed.

A study of contemporary boiler-room arrangements indicates that in many vessels the power is already available in the reserve capacity of the forced-draught and induced-draught fans. It is a common feature of design to deliver air to a boiler direct from a forced-draught fan and to discharge it, together with the products of combustion, through an induced-draught fan. If, however, the delivery from the forced-draught fan was delivered directly to the induced-draught fan and the boiler supply tapped therefrom by a suitable valve (Fig. 24), a high efflux velocity could be provided at any time the relative wind conditions demanded it. This could be done independently of the ship speed, because the valve would be operated to divert only the required amount of air to the boiler. The balance between the speed of the two fans must be computed in terms of the relative wind speed and the ship speed, and a suitable chart prepared for the boiler-room engineers. This would entail the addition of an anemometer to the ship's equipment, and it would require to be positioned as nearly as practicable in the free stream over the ship. The anemometer would give a remote reading of the wind speed and direction on an indicator in the boiler room, and it would be the responsibility of the engineers to adjust the speed of the fans in accordance with those readings.

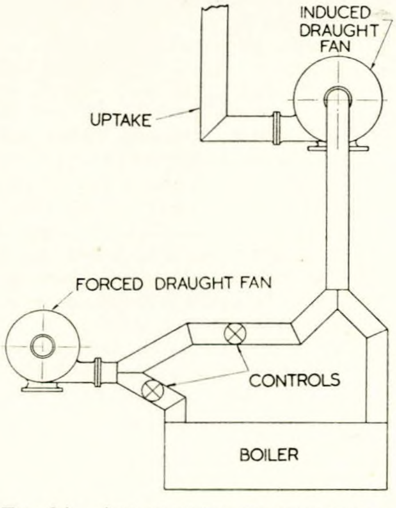


FIG. 24.—ARRANGEMENT TO GIVE A HIGH EFFLUX VELOCITY IRRESPECTIVE OF SHIP SPEED

In those vessels where the air supply to the boiler is obtained by increasing the boiler-room pressure above atmospheric, the solution is equally possible. A controlled inlet from the boiler room leading directly into the uptake will also produce an efflux velocity to give clear deck conditions within the limits of the design.

It follows, therefore, that either of these methods will afford the designer a means of obtaining the equivalent of full-power efflux conditions at all times and at any ship speed. When the ship is in harbour and both the relative wind speed and the ship speed are zero, nothing will keep the decks free from soot deposits other than a large asbestos umbrella.

### *Model and Full-Scale Comparison*

Manifold difficulties are encountered when attempting to record the pattern of the smoke plume under full-scale conditions. An escort of equal speed to that of the parent ship is required, from which the photographs can be taken, and this vessel must also carry a stabilized or articulated framework to support the camera. On board the parent ship other observers are needed to record the efflux velocity of the funnel gases, the speed and course of the ship, and the velocity and direction of the relative wind. Co-operation by signal between the two ships must be organized in order to ensure that they will be on parallel courses, at similar speeds, when the records are being taken. The fact that the whole operation requires to be conducted as a separate experiment introduces further complications in terms of time and cost. It is seldom possible to undertake these experiments during the acceptance trials of a vessel because of the many other tests on the ship's equipment then in operation, nor is it convenient to attempt such records when the ship is in commission because of the inconvenience to passengers.

Difficulty also arises in positioning the camera to photograph the plume from a station on board the ship herself. When the camera is trained aft it photographs the smoke astern as well as the smoke over the ship, so that it becomes quite impossible to determine where, on the ship, the smoke reaches deck level. When the camera is positioned aft and trained forward, the identification of specific parts of the plume is equally impossible. It becomes very much more convenient, therefore, to resort to visual observations, and many practical aids to this method may be devised. There is also the fact that the lower fringes may be scarcely visible, but they are usually above atmospheric temperature, while the sulphur dioxide content gives them a distinct odour, so that they may be detected by feeling or smell.

Areas of discoloration on the funnel and surrounding deckworks provide an indication of the extent and frequency of the descent of the funnel gases below the point of emission. More concise information on the velocity and direction of the relative wind under normal operational conditions at sea is still required in order that the velocity ratio of the model experiments may be adjusted to them.

We at the National Physical Laboratory are very much indebted to some of the leading shipping companies, whose kindly co-operation over the past few years has afforded us the opportunity of gaining a wider knowledge of full-scale smoke conditions. Much useful information has been obtained; and the impressions gained from this experience lead to the conclusion that the flow boundaries indicated by model experiments approximate very closely to those full scale.

### Acknowledgment

The above work has been carried out in the Aerodynamics Division of the National Physical Laboratory and this paper is published by permission of the Director of the Laboratory.

The author wishes to acknowledge his indebtedness to Mr. C. F. Cowdrey, for his valuable assistance with the experimental work and in the application to full-scale operation.

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## Appendix

### China Clay Solution for Chemical Reaction Experiments

| | |
|---|---|
| China clay .. .. .. | 400 gms. |
| Lead acetate .. .. .. | 80 gms. |
| Acetone .. .. .. .. | 1,200 c.c. |
| Glycerine .. .. .. | 20 c.c. |
| Water .. .. .. .. | 1,000 c.c. |

Dissolve the lead acetate in the water.
Add to china clay.
Add the acetone and glycerine.

The above quantities produce 1 winchester of the solution.

## DISCUSSION

**Mr. A. J. Merrington, C.B.E., B.Sc., R.C.N.C.** (Member of Council, I.N.A.) said that the Director of Naval Construction, Sir Charles Lillicrap, who was greatly interested in the problem of funnel design and smoke abatement, was unfortunately away on duty and much regretted that he was unable to be present.

The subject of the paper was eminently suitable for presenting to a joint meeting of the Institution of Naval Architects and the Institute of Marine Engineers. The problem it raised could only be solved by the naval architect and the marine engineer working together. If the marine engineer produced the objectionable funnel gases from his boilers, the naval architect put his bridges and superstructures in the way of the funnels, thus creating the turbulent airflow. He also necessarily placed some of his equipment, intakes and gear in the funnel gas stream.

The naval conditions affecting the problem of funnel design and smoke abatement were generally similar to those conditions found in merchant ships. There were, however, one or two important differences, including the following.

First, bad funnel gas conditions might have a serious adverse effect on the operational and fighting efficiency of a warship. The gear and equipment affected might include gun decks with open deck mountings, directors, control positions, radar; and, of course, in addition such problems as the drawing of funnel gases down into the engine and boiler room vents and into the ventilation system might also arise.

Next, warship speeds were higher than those of merchant ships in the main, and therefore higher efflux velocities of the funnel gases from the funnel were necessary to obtain the same relative clearance of smoke from the ship.

Thirdly, there was the aircraft carrier, a ship with special problems of its own—aircraft operating from the flight deck, the funnel on one side—and conditions very different from those of normal merchant ships.

Briefly, he would sum up naval experience as follows. Model experiments were considered to be valuable. The Admiralty had consistently relied on them, both in the design stage and when trouble was met with in the ships themselves. It might be appropriate here to make a reference to the excellent assistance and collaboration obtained from the National Physical Laboratory staff in these model experiments.

In general, naval experience confirmed the view of the authors that the most successful cure for funnel troubles was lengthening the funnel. One or two examples could be quoted as being of interest. In the "County" class cruisers there had been trouble after the ships were built, their gases sweeping down on the open gun decks aft. The funnels were lengthened 15 ft. and the trouble was successfully cured. In *York* and *Exeter* in the design stage, after model experiments, the two foremost funnels were swept together and the funnels were lengthened 10 ft. In *Vanguard* in the design stage, again after model experiments, both funnels were lengthened 8 ft. So much for the value of lengthening the funnels.

Cowls and chokes and various other devices had, in naval experience, produced sometimes complete and sometimes partial cure of funnel gas troubles. In *Vanguard* in the design stage cowls were planned and were considered to have some advantage as indicated by the model experiments. In the "Loch" class frigates where there was trouble, a cowl was fitted after some of the earlier ships of the class were built. The height of the cowl was 2 ft. 6 in. at the leading end and 6 in. at the after end. Results were satisfactory. In the "Hunt" class destroyers—"Hunt" class frigates, as they were now called—chokes were fitted after the early ships had given trouble. Results were satisfactory. In the "Leander" class cruisers the funnels were streamlined to reduce the gases coming down on the decks aft. On page J23 and in Figs. 12 to 14 reference was made to aerofoils and wind deflector plates. In the main, although these plates gave some alleviation of funnel gas trouble, they were not felt to be practical propositions. Either the plates were too large, or their effectiveness was only gained over restricted wind directions, and on the whole they were not considered very useful devices.

Reference was made here and there in the paper to following winds, and he would like the authors to sum up more precisely their experience of the effect of funnel gases in following winds and the possible cures. Funnel gases in following winds swept over the bridges and various control positions, and they were a great source of trouble. Anyone who had frizzled in strong wafts of following wind, laden with hot sulphurous smoke, would realize only too well how important it was to do something about it.

In the section of the paper on experimental technique, page J26, reference was made to the question of temperature effects and the buoyancy of the air. It was not clear whether in actual experiments on the model the air was heated up to the approximate temperature conditions obtaining in the ship, or whether the air in these model experiments was kept to normal air temperatures, with the steam or atomized paraffin indicators being injected. If cold air was used, he would like the authors to give some indication of what the effect was likely to be as between model and ship.

Lastly, he would like to ask the authors to go a little further into the future of funnels, and weather deck structure shapes. They had summarized the present position, but between them they must have amassed a lot of experience and it might be helpful if they would give some ideas on the future. He felt certain they would continue to press for and encourage the development of novel funnel shapes. Reference had been made in the paper to the French funnel and also to the air sheath. As Mr. Burge had mentioned, there was a great field yet to be explored. Was it possible that the gas turbine would produce just as many problems as the boiler-driven ship? Was it possible that the atomic age ahead might produce above the water-line a more smooth-hulled ship? The authors should be encouraged to give a little more information on the future of this subject.

**Dr. A. D. Third, B.Sc.,** said that the firm of ventilation and air-conditioning engineers with which he was associated was involved in the funnel question a number of years previously, when the problem of smoke and smuts entering the ventilation system had to be faced. Filters could be mounted at the inlets, but it was obviously better to prevent the ingress of smoke at all. Since that time his firm had carried out a large number of tests on model ships of all types with this aim in view.

In the summary to the paper, he observed that Mr. Ower considered the best shape of funnel to be cylindrical. This was rather a sweeping statement, although it had been modified later in the paper. In some ships, especially those with high poop decks, the problem lay within the 10 deg. wind inclination, and a moderate degree of streamlining of the funnel would appear to have some advantage, particularly as more equipment could be housed in such a funnel for the same width athwartships.

From Fig. 5(*b*), the effect of a raked top appeared to be very pronounced, and while he agreed in a general way with the effect, tests he had carried out did not show such a drastic downsweep in the boundary of the diffused smoke with a funnel of such moderate rake. Some degree of rake was almost standard practice in funnel design, and the effect recorded in the paper was therefore of considerable importance if it was actually reproduced on the full-scale ship.

He agreed that the frontal slots in the outer funnel casing, and other devices to take advantage of the momentum of the airstream created by the movement of the ship, were of no use whatever unless they had a very large area indeed and extended at least half-way down the front of the funnel. In other words, the stage was then reached where the outer casing ceased to exist as such, and a projecting inner funnel effect was obtained. His firm had designed a device of this type which gave an appreciable lift to the smoke. The design incorporated wing plates extending along each side of the outer casing of a normally dimensioned funnel. The plates were spaced from the casing in such a way that the gap towards the front was wider than that aft, and between the wings and casing were fitted deflector plates with an upward curve aft. By this means the stream of air created by the movement of the ship was made to enter the gap or slot at each side of the funnel, and was deflected in an upward direction. This arrangement was obviously most effective in a head wind, but it was also satisfactory in a wind having a yaw of 20 deg., or even more, since the effect of the gaps on the air stream could be likened to that of the slots in aircraft wings, which delayed the breakaway of the boundary layer and so preserved streamlined flow at considerable angles of yaw. The design also had the advantage of being effective in strong head winds, when the velocity ratio $s/v$ was reduced.

An obstruction such as a high bridge front could cause a steep rise in the smoke plume leaving the funnel, but the smoke was soon brought down again in violent eddies. In a full beam wind the effect of the large hull area presented was very similar. The smoke rose rapidly on leaving the funnel, but it billowed down to deck level soon after, although on many ships it would generally have time to pass overboard before the eddies were fully developed. Hence a beam wind could either cause a great nuisance on the deck, or give no trouble at all, according to the design of the ship.

He would be inclined to consider the possible courses of action to solve the smoke problem under two main headings: firstly, involving ships fitted with forced draught fans only; and secondly, involving ships fitted with both forced and induced draught fans. In the first case, which included mainly cargo vessels, it was generally impracticable to increase the gas velocity at the funnel top to any great extent, not because of the limitations of the fan, but in order to avoid appreciable positive pressures in the boiler casings. Again, it was hardly practicable in this class of ship to install fans and equipment specially to provide an annular discharge of air round the inner funnel top. One course of action would be to increase the height of the inner funnel by, say, 8 or 9 ft. with a taper to increase the velocity as much as possible, as mentioned by the authors. This gave the advantage, with a higher effective funnel, of a smaller frontal area to the wind at the top, in addition to the higher efflux velocity effect.

The unsightly appearance of a projecting inner funnel was of course a drawback to its adoption, and it had been suggested that the inner funnel could be telescoped, and raised only when necessary. Since the smoke nuisance was often worse when entering or leaving port, due to the low gas efflux velocities at reduced power, this was not an entirely satisfactory solution. The appearance could, however, be improved by having an open framework sloping upwards from the top of the outer casing to the top of the inner funnel, and some ships had been fitted with such a top.

The use of side wings, as he had already outlined, was also a means of tackling the problem without having recourse to auxiliary power.

For ships with both forced and induced draught fans—which were mainly in the express liner class—a projecting inner funnel would probably not be acceptable, and the best solution might be a high efflux gas velocity which could be maintained at low powers by a device such as that involving the by-passing of the boilers by part of the air from the fans, as suggested by Mr. Burge. The alternative of a high velocity annular jet should also be satisfactory. By either of these methods the funnel could be made to conform fully to the aesthetic demands of the naval architect.

His firm had also undertaken a number of tests on a model ship having two or three funnels, primarily to record the effect of the presence of the downstream funnels on the smoke plume from the forward funnel. With funnels of the usual semi-streamline form, no disturbance was observed under any operating conditions.

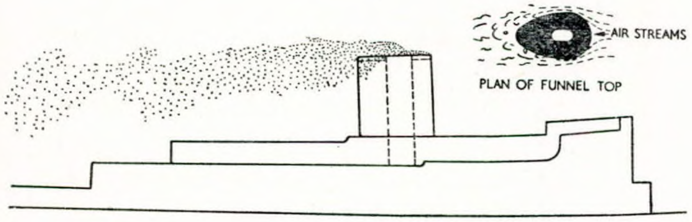
**Mr. H. J. Watson** said he would like to confine his remarks to describing a third method of curing the smoke nuisance.

He was, in principle, reluctant to employ additional power of any sort for the purpose of defeating the smoke enemy, and would consider doing so only if found necessary after other methods had been found inadequate. His investigations had shown that with modern conventional funnels probably the worst factor was not the downwash of airstream in the funnel wake, but the turbulence of low-pressure air over the whole area of the funnel top. This was particularly the case with the types of funnels which had become popular, i.e. surrounded by a large casing, often raked at the top, for aesthetic reasons, he believed. That type of funnel produced air conditions in the zone over the top of the funnel that were such as to cause an immediate and widespread diffusion and consequent rapid deceleration of the emitted smoke and soot. Model tests in a wind tunnel showed very convincingly that unless these bad conditions over the funnel top were eliminated they would greatly nullify the advantages of a high emission velocity.

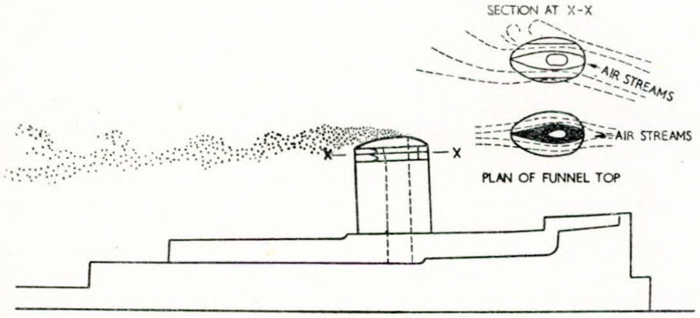
In the case of funnel designs employing a sunken top plate—the conventional method—it was useless to apply the velocity ratio $s/v$ as a basis for comparison because of the rapidity of the diminution in smoke velocity after leaving the zone of exit. Within a very few feet after leaving the smoke duct, i.e. the inner funnel, the smoke velocity might, for instance, be only one half the initial emission velocity. Yet it might be at this particular point the smoke first met the full impact of the wind.

In one set of tests in which a model conventional funnel was employed, he had provided attachments for two alternative tests: the first a coned smoke accelerator, such as the authors had shown, to replace the ordinary cylindrical inner funnel duct; and the second, a slightly domed cover plate to fit over the whole funnel top except, of course, for the opening for the uptake. When tested, the second alternative showed that the smoke velocity at a zone slightly above the efflux point was greater than at the same zone when the "accelerator" alone was fitted, in spite of the fact that in the latter case the actual emission speed was much greater. It was clear, therefore, that the ratio $s/v$ could only be precisely given when it referred to the relation of smoke speed *within* the uptake duct to the speed of wind approaching the funnel top, i.e. it was a ratio which existed *before* the occurrence of the event in which they were interested.

This funnel (Fig. 25), in its present form, consisted essentially of an elongated cowling, embracing the uptake duct, the cowl having truly streamlined sides and top plate. That was to say, the profile, in side view, was streamlined in form. Out of this top streamlined plate the inner funnel just protruded. The cowling extended over the full fore and aft length of funnel casing, and the width/length ratio was about one to five. The upper surface of the top plate was slightly convex. Within the space between each side of the cowling and the top of the normal funnel casing were arranged a number of horizontal and vertical plates which had for their purpose the guiding of entering air streams towards the aft trailing end of the cowling. As a result of fitting this cowl device, there was no low-pressure zone above the top of the funnel, and under average relative wind conditions experienced during a voyage there was no downwash of smoke behind the funnel. Actual vessels fitted with this type of funnel had proved very satisfactory in service, the results being especially gratifying when it was considered that no additional air or fan pressure was needed. The actual smoke emission speeds during tests under full power were not greater than 30 ft. per sec., which was quite a low average speed. The characteristic smoke trail was high and compact. It did not disperse to anything like the same degree as one expected to see from the conventional funnel. The benefits obtained not only concerned the smoke and gases from the main boilers, but also the smoke and gases from any auxiliary boilers, galleys, etc., provided they were vented from the top of the streamlined cowling.



Funnel of conventional design



Funnel with streamline top

FIG. 25. SMOKE TESTS WITH MODELS IN WIND TUNNEL

There was a further point which might not be very important but which counted in its favour: the heat of the gases which gave them buoyancy. The more compact the smoke trail could be kept the greater was the benefit obtained from the heat of the gases after leaving the top.

Such photographs that had been taken at sea seemed to show that with the conditions usually experienced the streamlined cowling at the top of the funnel was of considerable value, its chief virtue being that it prevented the sudden loss of gas velocity after leaving the top. There was no eddy at the top, and therefore there was no pull down or rapid dispersal of the smoke once it had left the top.

The effectiveness of the device was not restricted to conditions where the direction of wind was dead ahead or astern, but it appeared to be considerably beneficial under all relative wind directions up to about 30 deg. from the centre line of ship. See plan views of the lower illustration of Fig. 25. This widening of the effective range was probably attributable to the shape of the air passages between the vertical side plates and the contour of the cowling body.

There was, of course, much evidence in seaports of ships' funnels being blackened by smoke downwash and, since they were frequently cleaned, it was obvious that the downwash was not the result of abnormal weather conditions, but was a defect consequent upon design.

Scale models of actual ships when tested in a wind tunnel could be made to produce smoke trails and visible contamination closely resembling those observed while at sea. He had been interested to note that when working under conditions of closest similarity of smoke pattern between 1/100 scale models and full-scale ships the tunnel wind velocity was between 1 and 3 ft. per sec. and the smoke efflux velocity from 1 to 6 ft. per sec.

The opinions of competent observers in sea-going ships could be of great value, and in fact it was only by discussion with such experienced men that a full knowledge of smoke behaviour could be obtained.

For the future it would seem desirable to arrange for smoke trail photographs to be taken during ships' sea trials, when heavy smoke could be deliberately produced under widely differing wind conditions. So far, for obvious reasons, only a few such photographs had been published, but judging from the photographic evidence the indications were that the smoke trails from actual ships were rather better than those obtained from their small scale models.

The scale used for test models was often about 1/100 so that the findings of the correct similarity law was a matter of great difficulty. It was clearly necessary for the ratio $s/v$ to remain constant. It was equally important (i) for the height of the air stream deflected from obstructions to be in the true model scale; (ii) that the buoyancy effect of the hot funnel gases on meeting the heavier and denser wind must also be in correct scale; (iii) that the downwash effect must also be in the proper ratio.

It seemed impossible to find an exact criterion to satisfy all these requirements. The wind pressures were, however, so high in relation to the frictional drag that it seemed probable that one could ignore viscosity altogether. This meant one could discard the use of the Reynolds number and simplify the problem.

Requirement (i) should then be met at all speeds as neither $v$ nor $g$ were involved.

Requirement (ii) together with the speed of fall of particles suggested that $g$ was involved.

If this was the case the most suitable basis of comparison became $Lg/v^2$, i.e. $v \propto \sqrt{d}$, where $d$ was the scale. This was, of course, the normal Froude law of comparison.

Requirement (iii) was probably independent of viscosity, except possibly for a change at some critical Reynolds number.

**Captain (S) A. D. Duckworth, R.N.(ret.)** (Secretary, I.N.A.) said that during the war, when he went out to the Eastern Fleet, he was distressed to find sailing in the convoy a Frenchman with two rectangular funnels, a horrible affront to the nautical conventions: Could the authors say why a French designer should build a liner with two rectangular funnels?

Secondly, could they say whether any experiments had been carried out with ships which had more than one funnel?

So far they had described experiments with one funnel, but surely two or three might make an appreciable difference.

Lastly, he hoped the authors would follow up this question of the conditions in a following wind. He had vivid recollections in the first World War of going to his action station in the foretop of H.M.S. *Lion*, which was practically immediately above the forward funnel. Climbing over the forebridge guard-rails, in one's thickest pair of gloves, one took a deep breath, closed one's eyes, and raced up the vertical strut of the tripod mast (seemingly just not glowing red hot). Immediately engulfed in blistering sulphurous fumes, one arrived spluttering and choking in the foretop, to find that also filled with blinding smoke, conditions hardly conducive to accurate enemy observation, or to the gunnery officer's control of the main armament.

**Mr. L. Baker, D.S.C.** (Member, I.Mar.E.) wrote that the distribution of particle sizes ejected from the funnel must largely be controlled by the oil particle sizes sprayed into the furnace by the atomizer. It was significant that there was a wide divergence in the effects of smoke with the type of oil-burning apparatus in use. More attention should be paid to the use of high pressures for atomization and to the adoption of efficient atomizer tips.

In this connection it was difficult to see how combustion control could affect the problem since the troubles were caused by factors largely outside the control of the engineers. If the remark were intended to imply that combustion control would ensure smaller particles, then it must be stated that the converse was more likely to be true.

With reference to the remark in Part I, "The upward momentum of the funnel gases can be increased for a given uptake diameter by increasing either their temperature or their velocity," it was difficult to see how, with a given uptake, it was possible to increase the velocity of the gases without increasing their temperature since at this stage the increase of momentum by means of additional air had not been considered.

At a later stage the author indicated the deleterious effects resulting from operation at reduced speed. This, however, was of less significance in most merchant ships, although it was of course an essential requirement for naval vessels.

In the same section the author suggested that a variable outlet area could only be provided at the expense of other difficulties of a different kind. This remark was obscure, and while he did not think such a device would normally be justified there was no doubt that it could be developed satisfactorily, as would be seen from Fig. 28.

It might be of value to quote the experiences in ships (Figs. 26 and 27) of his own company. The length of these ships was 515 ft. 5 in.; height of top of funnel was 82 ft., and that of the top of the higher structure 52 ft.; the funnel was oval with a major axis 24 ft. and a minor axis 17 ft. The ships had a service speed of about 18½ knots.

No great difficulty was experienced when steaming into a head wind. The down draught, however, with a relative wind just forward of the beam was so great that boat covers of the first ship were ruined in one voyage. In subsequent ships the velocity at discharge from the funnel was increased to about 100 ft. per sec. at 280° F. (see Fig. 28), and this appeared to have overcome the problem completely, with the exception that the tops of the Sampson posts on the poop were fouled when soot blowers were used with a head wind (see Fig. 26).

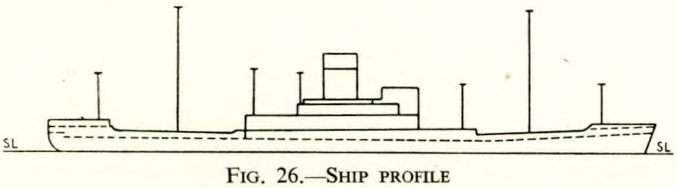
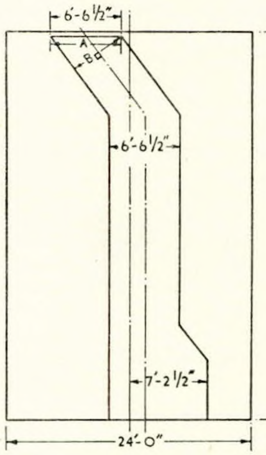
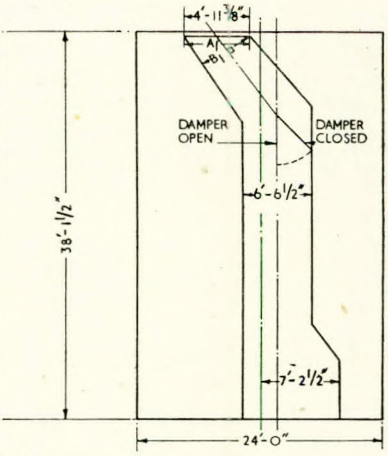


FIG. 26.—SHIP PROFILE





Scale: ⅛ in. = 1 in.

FIG. 27.—ORIGINAL FUNNEL

Area at "A," 37·5 sq. ft.
Area at "B," 34·0 sq. ft.

FIG. 28.—MODIFIED FUNNEL

Half area at "$A_1$," 11·8 sq. ft.
Half area at "$B_1$," 9·7 sq. ft.

**Mr. W. Waters, B.Sc.** (Associate Member, I.N.A.) wrote that the shape of funnel evolved by Messieurs Valensi and Guillonde represented a new approach to the problem of smoke nuisance. Whereas most funnel shapes were designed to minimize the effect of the trailing vortex created by the funnel, this particular design used the vortex to carry the smoke clear of the deck.

Applying this principle in a somewhat different manner, it would be interesting to examine the effect of combining the funnel and foremast with a view to compelling the bound vortex to travel upwards, beyond the boundary of the turbulent zone, before breaking away and trailing downstream, taking with it the funnel gases.

Apart from aerodynamic considerations the shaped plate construction of the mast would produce a structure of considerable strength and pleasing appearance. This type of construction should prove advantageous in destroyers, where the foremast and funnel were invariably placed close together.

On page J23, Mr. Ower stated that complete correlation between model and full scale had yet to be established. An early solution to this problem was vital if the use of model experiments in funnel design was to be extended; and without a reliable technique for testing models there could be little hope of interesting ship-owners in novel funnel shapes and devices.

Although complete similarity could not be reproduced in one test, it appeared that near similarity of flow patterns existed when (*a*) the model funnel gases had the same density as the ship funnel gases; (*b*) the temperature of the model gas was such that either

$$\theta_m = \frac{R_s}{R_m} \times \frac{1}{\lambda} \times \theta_s$$

or

$$\theta_m = \frac{K_s}{K_m} \times \frac{1}{\lambda^{3/2}} \times \theta_s$$

depending upon which of the two factors $R$, the gas constant, or $K$, the coefficient of thermal conductivity, was assumed to have no effect.

$R$ and $K$ were used to denote the composition and rate of cooling of the funnel gases, respectively; and $\lambda$, the ratio of the lengths of ship and model.

The effect on the flow pattern of lack of similarity between one or more of these needed to be determined precisely, although the authors might be able to give some indication of the progress already made.

Mr. Burge's remarks on page J26 in connexion with the paraffin smoke generator seemed to suggest that the density of the model funnel gases was made equal to that of the surrounding atmosphere. This did not agree with the density relationship suggested by himself, which must be satisfied if the buoyancy forces and the horizontal dynamic forces were to follow the same law of comparison. It would be interesting to have the authors' opinion on this point.

Finally, could the authors state whether tests had been made with models of the same ship, built to different scales, in order to determine the magnitude of the "scale effect"?

It was unfortunate that attempts to improve the outward appearance of a ship should introduce so many new difficulties, but the quest should be continued until a funnel design had been found which was both mechanically sound and pleasing in appearance. The authors were to be complimented for their contribution to this end.

**Professor J. Valensi** wrote that since the reading of the paper two ships belonging to the Compagnie de Navigation Mixte had been fitted with the French type of funnel described by Mr. Ower under "Methods of Prevention (*c*)."

On one of these ships, previously fitted with a conventional funnel, there was some inconvenience due to smoke, and it was completely cured when the funnel was replaced by one of the new design. This favourable result led the company to incorporate a funnel of the new type in the design stage of the second ship.

The effectiveness of the new funnel was shown by the fact that, after two months of operation, the two ships were as clean as when newly painted.

It might be of interest to add a few remarks based on practical experience with this funnel:—

(1) The funnel worked well whatever the magnitude of the efflux velocity; it was therefore not necessary to increase this velocity at high values of the relative wind speed in order to get a value of $s/v$ of 1 or 2.

(2) The smoke emerging from the uptake showed no signs of being sucked down into the low-pressure region behind the funnel.

(3) The jet preserved its individuality in the air for a considerable distance aft of the ship.

(4) The heavy solid particles did not fall on to the deck, as they were retained in the core of the tip vortex, where the pressure was lower than that of the atmosphere and the relatives peed higher than that outside the vortex.

This full-scale confirmation of the model results mentioned by Mr. Ower was made possible by Monsieur Gravier, Chairman of the Compagnie de Navigation Mixte, who asked the Société des Forges et Chantiers de la Mediterranée to fit the funnel on the two ships.

### Authors' Reply

**Mr. Ower,** replying to the discussion, said it appeared from Mr. Merrington's remarks that very often a moderate increase in the height of the funnel produced a substantial improvement; and he had quoted three funnels in which the height had been increased, in one case by 15 ft., in another by 10 ft., and in a third by 8 ft. From the point of view of appearance, it was not the actual increase in height that mattered, but the increase expressed as a ratio of the downwind dimension of the casing. It would be interesting if Mr. Merrington could quote that ratio for the three cases he had mentioned, because it would probably show that very often a good improvement could be obtained with very little sacrifice in appearance, to which the shipowner might not object.*

Mr. Merrington had pointed out that deflector plates were not a practical proposition. This had been implied in the paper, but it had been thought that the available information on these plates, for which he was indebted to the Admiralty, should be included in the paper, for completeness, because, although not practical, they were certainly effective.

Mr. Merrington had asked the authors to forecast future shapes of funnels and superstructures. It was always dangerous to prophesy, but certainly all known types of propulsion produced an exhaust of some kind or other, which would have to be got rid of. In this connexion, he understood from owners of motor ships that although the smoke was not visible, they still had the same problems of funnel design and exhaust disposal as in ships with oil or coal-fired boilers. The same would probably be true with gas-turbine propulsion. As regards propulsion by atomic energy, no one knew what form this would take at the moment, and therefore speculation would be useless.

Dr. Third had taken him to task for over-emphasizing the advantages of the cylindrical funnel. Perhaps at first sight the summary of the paper was too drastically worded in this respect, but he thought that there was little doubt that, if one accepted the arguments of the paper, the conclusion that the cylindrical funnel was best when all conditions were taken into account was inescapable.

Dr. Third had also suggested that the bad effect of the raked top shown in Fig. 5 had been exaggerated. As he was indebted to the National Physical Laboratory for that diagram, he would leave Mr. Burge to deal with this point. He had been interested in Dr. Third's funnel with the wing-plates, whose action was perhaps similar to that of the Handley-Page slot on aircraft. Although Dr. Third had remarked that it was satisfactory in the wind having a yaw of 20 deg. or even more, there must be an angle at which it ceased to be effective, and so in that respect it was inferior to an increase of height or of efflux velocity, neither of which was subject to this restriction.

He had also been very interested in the new type of funnel described by Mr. Watson, of which the only previous information he had had was a very brief note published in the technical shipbuilding Press. In view of Mr. Watson's experience on the effectiveness of this funnel, he was sorry that particulars had not been available for him to be able to include it in his description of successful devices for curing the smoke trouble; but as no information had been published he had been unable to refer to it in the paper. One of its advantages was that no extra power was necessary, as Mr. Watson said that there was no need to increase the efflux velocity of the funnel gases. Mr. Watson had said there was no increase in height, but added that in most of the cases he was called upon to investigate the funnel was not sufficiently high to begin with. Therefore he usually lifted it up a little, at the same time as putting a top on it.

The author thought that it was probable that Mr. Watson's funnel had a better top, but he wondered whether some of the improvement was not due to the increase in height.

**Mr. Watson** said that some of it was.

**Mr. Ower** said that a number of speakers had raised the question of the effect of buoyancy due to the temperature of the smoke, and its effect on the prediction of the behaviour of the full-size funnel from experiments in the wind tunnel. Mr. Burge had stated the conditions to be fulfilled on page J26 of the paper under the sub-heading "Effect of Buoyancy." He would therefore leave Mr. Burge to make any amplifications of these remarks that he considered necessary.

Mr. Watson had said that the speed of testing in wind-tunnel experiments was too high. In his opinion, it was fundamental that, apart from temperature effects, in order to get the same flow pattern on the model as on the full scale, the Reynolds number of the test would have to be the same as that of the full scale. This would mean that if one were working with a model of 1/100 full scale, the speed of the relative wind would have to be 100 times that experienced at

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* The following values for these ratios were deduced from information supplied by Mr. Merrington after the lecture. "County" class cruisers 1·4 for forward and after funnels, 0·9 for amidships funnel; *York* 0·5 for forward funnel, 1·0 for after funnel; *Exeter* 0·5 and 0·7; *Vanguard* 0·4 for both funnels.

sea. This condition was obviously impossible to fulfil, but it did show that so far from the speed in the wind tunnel being too high, it was if anything too low. It was only because the nature of ship models was such that the flow around them changed very little with Reynolds number that wind-tunnel experiments were possible at reduced speeds. In any case, the ultimate criterion of the usefulness of wind-tunnel experiments was whether the results obtained from them were reproduced sufficiently closely in the actual ship. All experience so far available indicated that this was the case, and that, if anything, the wind-tunnel experiments erred on the pessimistic side; that is to say, that one could expect a full-scale result at least as good as the wind-tunnel experiments indicated. He was interested to see that Mr. Watson had come to the same conclusion.

**Mr. Watson** said he had pointed out that the best speed for testing was in his experience below that which a lot of authorities had used. The air/smoke velocities are often referred to as a ratio but it did not seem to him to be a sufficient basis of comparison. The actual velocities did have a bearing. He handed Mr. Ower a photograph saying that this gave an indication of the appearance. Photographs were taken at a tunnel velocity of 2 ft. per sec. Any other speed gave a false appearance compared with the real shape. It seemed that the Reynolds number was not the way to approach the matter.

**Mr. Ower** said he was unable to give any aerodynamic reason for the rectangular funnels seen by Captain Duckworth; he could only suggest that it was one more unfortunate outcome of the pernicious tendency, particularly prevalent at present in the various forms of art, to regard anything that flouted conventional standards as necessarily an improvement.

Referring to Mr. Baker's comments Mr. Ower was sorry that in his remarks on soot and ash he used the term "combustion control" rather loosely. What he meant by combustion control was some method of ensuring that no solid particles were present in the funnel gases. As Mr. Baker correctly pointed out, the best method of ensuring this was to pay more attention to the conditions of atomization.

He thought Mr. Baker had been a little unjust in taking exception to the remark about the possibility of increasing the momentum of funnel gases by increasing their velocity. This was an introductory remark, in which he was enunciating the principle, and practical means of increasing the momentum were considered later in the paper.

He was interested to learn of the successful cures of the smoke trouble quoted by Mr. Baker, which were effected by increasing the discharge velocity from the funnel, and also in the device illustrated in Fig. 28 for effecting this increase of velocity.

Mr. Waters had interpreted the remark on p. J23 about the correlation between model and full scale in a much wider sense than that in which it was intended. If this remark was not taken out of its context, it was quite clear, he thought, that it only applied to the present position regarding the air annulus, which had not yet been tried out on the full scale, and which was very difficult to test on the model scale because of the small size of the annulus. The remark that full-scale verification was needed referred only to this particular case. As he had said in the paper, and in his replies to other contributors to the discussion, there was ample evidence already in existence that full-scale results could be confidently predicted from model experiments on the smoke trouble. The technique was quite reliable, and so Mr. Waters' fears were unfounded.

Mr. Waters also asked whether tests had been made with models of the same ship built to different scales. As far as he knew this had not been done, nor did he think it necessary, because the agreement between model and full scale was so good that it was extremely doubtful whether any significant differences would be observable between the behaviour of two models of different size.

He was very interested in Professor Valensi's remarks. The type of funnel described made use of a principle that had not previously been applied to this purpose. In view of the encouraging experience reported by Professor Valensi, it would be most valuable if he could arrange for the publication of a fully illustrated description of the ships, if possible giving a direct comparison between their behaviour before and after fitting the new funnel.

**Mr. Burge,** in replying to the discussion, said Mr. Merrington had referred to the temperature effects on experimental plumes. It was explained in the paper that the wind tunnel investigation of temperature effects required a very low wind speed and a correspondingly low efflux velocity. Difficulties arose in measuring and controlling small quantities of discharge and maintaining temperature levels in small model uptakes; furthermore, the velocity distribution across the working section of the wind tunnel tended to become erratic at low wind speeds. It was necessary therefore to study temperature effects as a separate experiment on the funnel alone. With small models of the complete ship it was convenient to use a range of wind speeds from 10 ft. per sec. to 40 ft. per sec., and at these speeds any temperature in the effluent was so quickly lost that the gain in height due to it was almost negligible. Thus practically all of the experiments to define the plume boundaries had been made with cold plumes. Because the vortices in the lower boundary did not remain located along the plume, it was necessary to define the general path of the lower boundary by a time exposure rather than by instantaneous exposures. Exposures had been made over a wide range of wind speeds and efflux velocities at the same velocity ratio and, apart from the greater diffusion of the smoke at the higher wind speeds, the plume pattern had remained practically the same throughout the range.

The turbulent flow around a ship's structure was determined by the shape and scale of the structure, and the rate of diffusion of the funnel smoke, being determined by this turbulence, was reasonably similar on an accurate model of the ship under similar conditions of wind and efflux speeds, apart from the effects of temperature. Thus the usual Reynolds number involving kinematic viscosity was of little significance. With regard to the effect of temperature, this was determined by the relation between the forces of buoyancy and the pressure gradient in the flow due to obstructions in the path of the wind and funnel gases. Model and full scale would correspond if $v^2/lT$ were the same for each; $l$ being a typical length and $T$ the difference in temperature between the gas at the funnel exit and the atmosphere.

The full-scale funnel should give better results than the photographic records of the model for two obvious reasons, firstly, there was the added gain in plume height due to the heat of the funnel gases and, secondly, there was the gain in velocity ratio the ship experienced in turning across the wind, which was not usually allowed for in the wind tunnel experiments. For example, when a ship was steaming at 15 knots into a headwind of 20 knots, the relative wind speed over the ship would be 35 knots, but at 30 deg. out of wind, the relative wind speed would be 31½ knots. As wind tunnel experiments were usually of a comparative nature to determine the advantage of one funnel design over another, it was more convenient to maintain the same velocity ratio throughout the angular range of wind direction, rather than to evaluate the corresponding relative wind speed at each angular setting.

In reply to Dr. Third, he would agree that, at first view, the discoloration of the funnel with a raked top did appear to be exaggerated, but, in point of fact, the diagrams of Fig. 5 were taken from the actual $H_2S$ staining obtained at wind ahead on a model of a modern vessel. The flowlines approaching the funnel in a wind 30 deg. off the bow were very different from those at wind ahead, while the funnel itself presented a much large projected area to the wind and, therefore, it had a much larger wake. Under cruising conditions the efflux velocity was generally high enough to raise the upper boundary of the plume well clear of the ship, but the lower boundary invariably descended into the disturbed region in the lee of the funnel at all velocity ratios below 1/1. At sea, the lower boundary had been observed to break clear from the funnel outlet and, after travelling 20 ft. or more downwind, to be entrained into the wake and return right to the lee face of the funnel. In a 90 deg. wind the main plume got well clear of the ship, but the fact that some of the diffused smoke from the lower boundary returned on board might be amply verified by the smell of the $SO_2$ content, which might be detected along the lee decks.

Cargo ship funnels could be fitted with either a hinged or sliding damper plate at the point of emission to adjust the area of the outlet in relation to the ship's speed and, alternatively, the speed of the relative wind. Objections to the practicability of this method had been put forward in as much as the damper mechanism might become eroded or fouled by soot after a period of steaming at a cruising or lower speed, and so impair the handling of the ship if full power should be required at short notice. Provided that the operating mechanism could be adequately protected these devices could be very effective. It must not be overlooked that additional power was required to discharge the same volume of effluent through a smaller outlet.

Captain Duckworth had asked about ships having more than one funnel. A number of experiments had been carried out on twin funnels; chiefly on naval vessels. In mercantile vessels where the funnels were less likely to be affected by superstructure up wind of them, the after funnel was generally immersed in the aerodynamic wake of the forward funnel. This interference extended over a wide angular range of wind direction, depending upon the spacing and size of the funnels; in many instances, the ship would require to be more than 20 deg. out of wind for the after funnel to be free of the interference.

In the design of ship's funnels it was necessary to bear in mind that the essential factor was that which ensured complete elimination of smoke from those parts of the ship where ventilator intakes were installed. This must apply to all directions of relative wind, whether or not the effluent from the funnel was visible.

The authors were indebted to Mr. Baker for the details of his application of a damper to a full scale uptake. It would have been preferable to have had the damper at the outlet and thereby avoided the aerodynamic losses consequent upon the sudden change of direction and velocity at the bend. The dimensions of Figs. 27 and 28 enabled them to derive a rough approximation of additional H.P. required to discharge the gases at 100 ft. per sec. through the reduced outlet from the relationship

$$\text{H.P.} = \frac{\rho}{2 \times 550}(A_2V_2^3 - A_1V_1^3)$$

Assuming a value of $\rho$ for smoke as 0·002 slugs per cu. ft. they got:—

$$\text{H.P.} = 16{\cdot}2$$

This represented the difference in jet H.P. at the funnel outlet; there would be also the additional drag losses in the modified uptake.