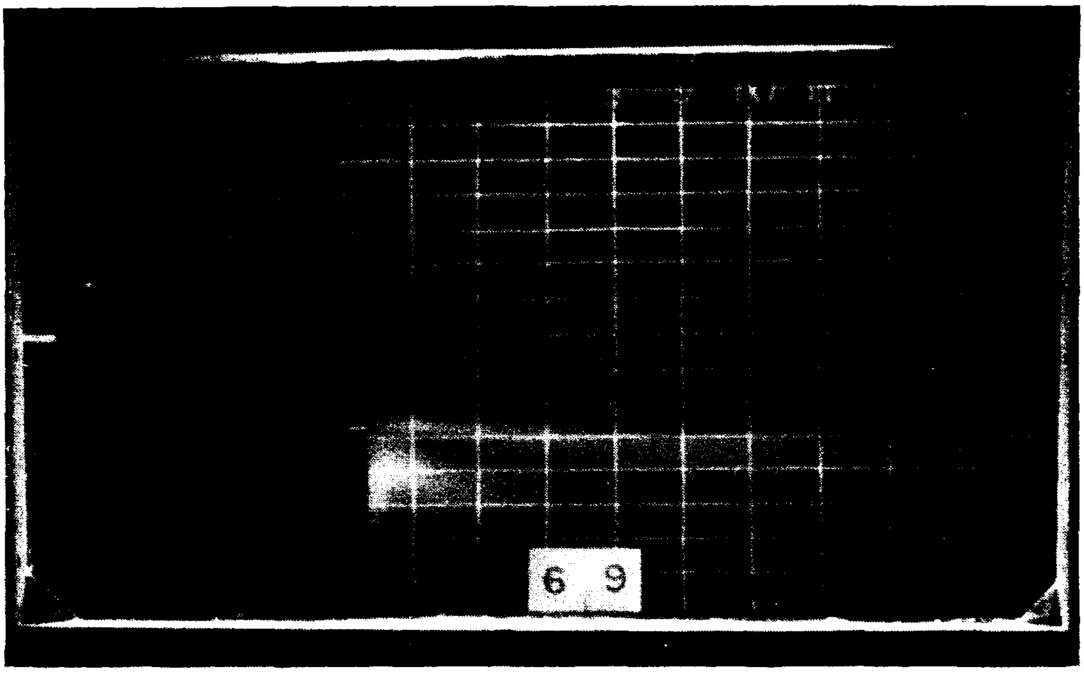


FIG. 1—FREESTANDING CYLINDRICAL FUNNEL SHOWING DRAWDOWN

THE DESIGN OF FUNNELS

BY

LIEUTENANT-COMMANDER T. F. CRANG, R.N. (RTD.), M.SC. (ENG.), A.M.I.MECH.E., M.I. MAR.E.

The Author of this article will perhaps be better known to readers as a serving officer and a one time Editor of this Journal. He retired in 1954 *to take up the newly created post of Head of Research and Development at Messrs. J. Samuel White and Company Ltd., of Cowes.*

In recent years experiments have been made for the Admiralty on means of keeping funnel gases and smoke clear of the decks of warships. These experiments have been carried out on ship models in wind tunnels at the National Physical Laboratory, and the predictions made from the model tests have usually been confirmed by full-scale trials.

The writer believes that a low-speed wind tunnel for the study of this, and allied problems, is a necessary adjunct to the design office of a shipyard.

This article is written to describe the rationale of such tests and to help naval engineers to appreciate the aerodynamic factors involved in the design of a satisfactory funnel.

The Background

The funnels of ships built at the beginning of the century were made high enough to create sufficient natural draught to keep the furnaces under a negative pressure. The funnel tops of the *Mongolia*, built in 1904, were almost 100 feet above the water. The boilers of the *Lusitania* were spread out over a fore and aft distance of 366 feet and required four funnels.

The public came to associate three or four high funnels with large fast ships. The funnels, in fact, came to assume the characteristics of the figurehead of a sailing ship.

With the introduction of water-tube boilers and turbines, the machinery became more compact ; the most powerful ships needed only two funnels and those of medium power only one. The prejudice of the public mind in favour of multiple funnels resulted in ships being fitted with dummies; for example, the *Titanic*, in 1911, had one dummy funnel.

During the 1920's the influence of automobile and aircraft design led to a change of attitude. The concept of streamlining became widely known. Designers were allowed to decrease the number of funnels, but, as if to compensate for lack of numbers, they aimed at the impression of squat power. Finally, as the public came to equate streamlining with efficiency, even in stationary objects, the trend affected ship design and in some recent ships he funnel has been reduced to a simulacrum of its original form.

The craftsman who made the figurehead could give his artistic sensibilities ull play without affecting the efficiency of the ship. In some cases, however, he ship designer seems to have forgotten that a funnel has a basic engineering unction.

The funnels of some recent ships have failed to fulfil this function, and these hips are notorious for the quantities of funnel gas, soot, and unburnt fuel vhich descend to the decks and enter the ventilation systems. Although the cult of streamlining has not been carried so far in warships, funnels have become ower and superstructures higher. More care is now required, therefore, to nsure that warship funnels can carry the discharge clear of bridges, gun-crews, nd lookouts.

In the design of funnels, the engineer and aerodynamicist should work with he naval architect to blend the functional with the aesthetic.

he Theory of Model Tests

From the principles of dimensional homogeneity and dynamical similarity it an be shown that, where both the effects of gravity and viscosity are involved 1 the interaction between a solid and a fluid, the resistance to flow is given by :—

$$R = l^2 \; v^2 \; \rho f\left(\frac{\nu}{vl} \cdot \frac{lg}{v^2}\right)$$

Vhere R = resistance to flow
l = a characteristic linear dimension
ρ = density of the fluid
ν = kinematic viscosity of the fluid
v = relative velocity between fluid and body
g = acceleration of gravity

It is necessary for dynamical similarity that each of the terms of the function f hould have the same value for the model as for the original.

If, as is usual in practice, the model and the original operate in the same edium, either air or water, ν and g are both constant. For similarity, therefore, oth vl and l/v^2 require to be constant. Since this is impossible, it follows at the phenomena due to viscosity and those due to gravity occurring around e original and the model, in the same fluid, cannot simultaneously be made ynamically similar.

It remains to be seen whether either of the terms of the function f may reasonbly be neglected in order to give a useful practical approximation.

Practical Correlation of Model and Original

The resistance of a surface vessel is one case in which both gravity and viscosity are involved, and in which, therefore, no two corresponding speeds will satisfy all requirements. The speeds which give geometrically similar wave formations around similar ships will not give similar stream lines in parts of the systems subject to viscous flow. If the influence of one of these parameters greatly outweighs that of the other, however, valuable practical results can be obtained by choosing the corresponding speeds with reference to the important factor. Thus, in tank experiments on models, the corresponding speeds are chosen with reference to the gravity effects, that is, to the wave and eddy effects and are proportional to the square root of the corresponding linear dimensions.

Both gravity and viscosity are involved, also, in the case of a ship's superstructure with the funnel discharging hot gases into the airstream. Here, the superstructure and funnel are subject to viscous flow, while the hot gases leaving the funnel are subject to gravity.

The path of the smoke or gases as they leave the funnel is largely determined by the pattern of the airflow caused by the bridge structure, in the wake of which the funnel usually stands. This pattern is related to the aerodynamic resistance of the structure.

The resistance of bluff bodies is bound up with the formation of layers of discontinuity. If, as is usually the case with sharp-edged bodies, the points at which the layers of discontinuity begin are fixed, the resistance is found by experiments to be constant for a wide range of conditions. Thus, for example for smooth circular discs normal to the airstream there is no appreciable alteration in the resistance for values of Reynolds number ranging from 2,000 to 500,000, and it may be taken as certain that no change in behaviour would occur even for much higher values.

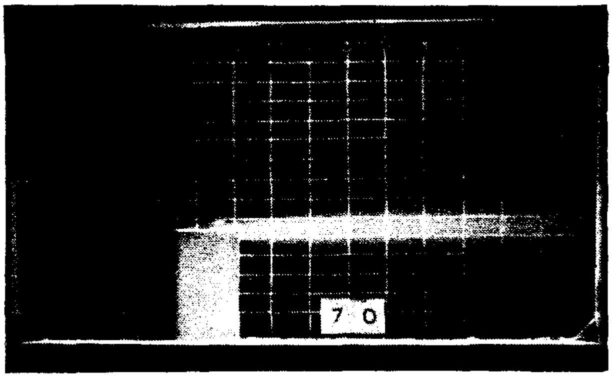
What is true of the resistance coefficient is also true of the distribution of pressure. Eiffel made measurements of pressure distribution on three geometrically similar structures with dimensions proportional to 1, 6·25, and 50. In spite of this great difference in size, the correspondence of pressures at similar points was very close.

Other factors being equal, the Reynolds number applicable to a full-sized vessel will be 48 times that for a 1/48th scale model. It has been seen that Reynolds number ratios of 250 to 1 do not appreciably affect the resistance coefficient, which, therefore, can be taken as the same for both model and original. This implies that the aerodynamic pattern for the model and for the full-sized vessel is dynamically similar. The Reynolds number term in the function f can, therefore, be neglected.

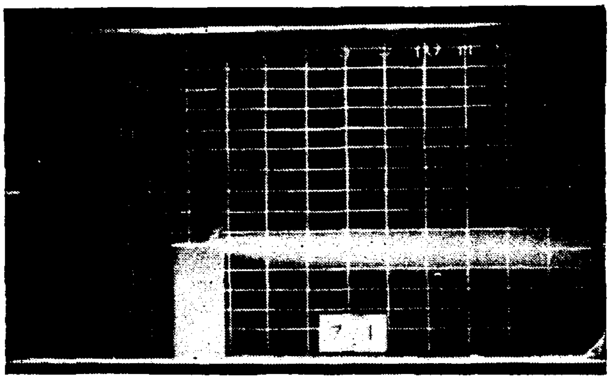
There remains the term due to the buoyancy of the smoke or gas plume involving the l/v^2 term. Unfortunately, there is little possibility of conducting model tests at the relative wind speeds given by this factor. For example, to represent a 10 ft/sec wind speed with a 1/48th scale model, a model wind speed of $10/\sqrt{48}$, or 1·42 ft/sec would be required to reproduce the pattern of the smoke or gas plume. It would be very difficult to obtain a uniform tunnel velocity at such a low speed and even more difficult to measure it with sufficient accuracy.

Since neither of the theoretical requirements can be fulfilled in practice, it is necessary to seek some simpler basis of correlation between model and original. This is found in the ratio of the funnel gas or smoke efflux velocity S to the relative wind velocity V. Since the gas and wind flow are two intersecting streams of fluid, the ratio of the velocities should be made the same for the model as for the original.

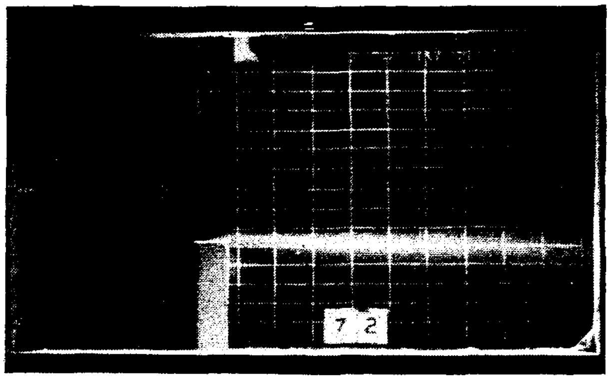
It has been found, in practice, that the S/V ratio is the most important factor in determining the path of the smoke or gas plume. Since there is little Reynolds number, or scale, effect, it may be supposed that, whatever the absolute velocities S and V, the path of the plume will be the same for equal S/V ratios. Wind tunnel tests support this conclusion.



(*a*) THICKNESS/CHORD 0·56



(*b*) THICKNESS/CHORD 0·34



(*c*) THICKNESS/CHORD 0·31

FIG. 2—FREESTANDING FUNNEL WITH STREAMLINED OUTER CASING SHOWING REDUCTION OF DRAWDOWN

The Effect of Obstructions

The shape of the plume of gas or smoke from a funnel is affected by :—

(*a*) the S/V ratio,

(*b*) the temperature of the funnel gases,

(*c*) the form of the superstructure upwind of the funnel.

Consider the case of an isolated or ' freestanding ' funnel emitting gases at atmospheric temperature and at a very small velocity. Then, for any wind velocity, the smoke plume would be horizontal except for a certain ' drawdown ' into the low pressure region formed behind the funnel. This effect is shown in FIG. 1.

The effect of streamlined casings of decreasing thickness/chord ratio in reducing the drawdown is shown in FIG. 2 (a), (b), and (c). Thus, for a stream-lined freestanding funnel operating under these conditions, a horizontal line about half a diameter below the funnel top will define the limit below which the smoke or gases will not fall. An increase in the efflux velocity, and thus in the momentum of the funnel gas, giving an increase in S/V ratio, will raise the path of the plume.

A higher funnel gas temperature, by making the plume more buoyant, will have the same effect. Unfortunately for the funnel designer, the more efficient the boilers become, the lower is the funnel gas temperature. Ships fitted with economizers may expect more trouble with smoke clearance than their less economical forerunners. The temperature of the funnel gas is not, however, variable as far as the funnel designer is concerned. Thus, whenever smoke or gases descend to the decks of a ship abaft the funnel, the trouble is due to the form of the hull and superstructure upwind of the funnel.

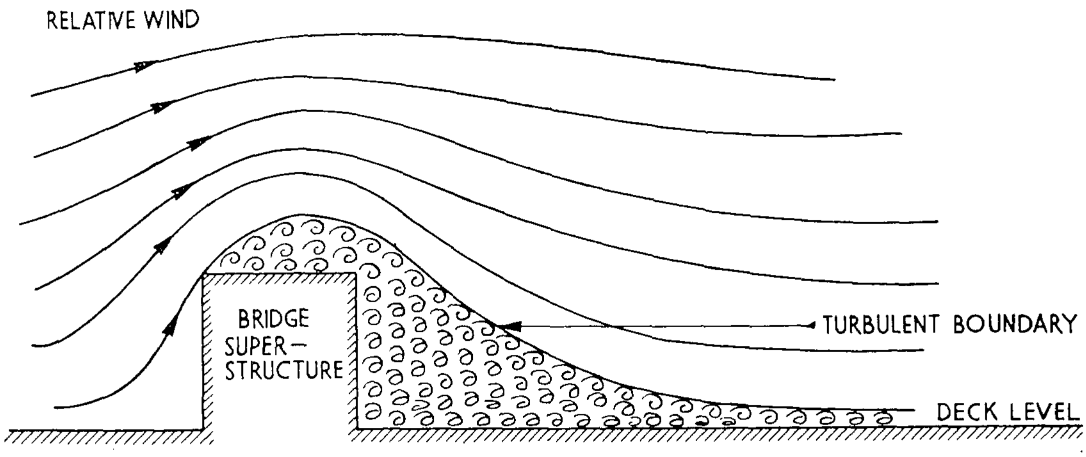


FIG. 3—EFFECT OF WIND STRIKING SUPERSTRUCTURE

The bridge structure of a ship in a head wind forms an obstacle from which a turbulent boundary originates, as shown in FIG. 3. The course of the boundary layer depends upon the form of the superstructure. Above the turbulent boundary the air flow continues smoothly, while the space between the boundary and the bridge structure is filled with intense eddies. Eventually the turbulent boundary descends to the level of the deck. The effect is shown in FIG. 4, in which a jet of steam is seen impinging on the front of the superstructure, separating from the top of the bridge, and forming a region of eddies behind the obstruction.

Low-velocity gases from a funnel top below the turbulence boundary will be caught in the eddies and rapidly diffused into the space between the turbulence boundary and the deck. The lower edge of a low-velocity gas plume from a funnel top in the turbulence boundary will follow the boundary. Low-velocity gases from a funnel top above the turbulence boundary will only descend to the deck if the turbulence boundary reaches the deck level before it is clear of the ship. As the S/V ratio is increased so the lower edge of the smoke plume is raised progressively above the turbulent boundary.

Therefore, to avoid the descent of smoke or gases to the deck, the funnel top should be above the turbulent boundary and the S/V ratio should be maintained above a certain limiting value. At present, this value can only be found by experiment.

Wind Tunnel Technique

Though crude by aerodynamic standards, the low-speed wind tunnel, with which the writer is concerned, is adequate and effective for investigations of this type. It is a suction tunnel 25 feet long, with a working section 2 feet square, the wind speed being regulated by throttling the exhaust. The tunnel is shown diagrammatically in FIG. 5.

Air is drawn in through a converging entry portion and passes through a honeycomb to destroy coarse turbulence. The air velocity can be measured by three methods :—

(*a*) by an anemometer traversed horizontally and vertically across the tunnel,

(*b*) by a pitot tube connected to a sensitive Krell type inclined manometer,

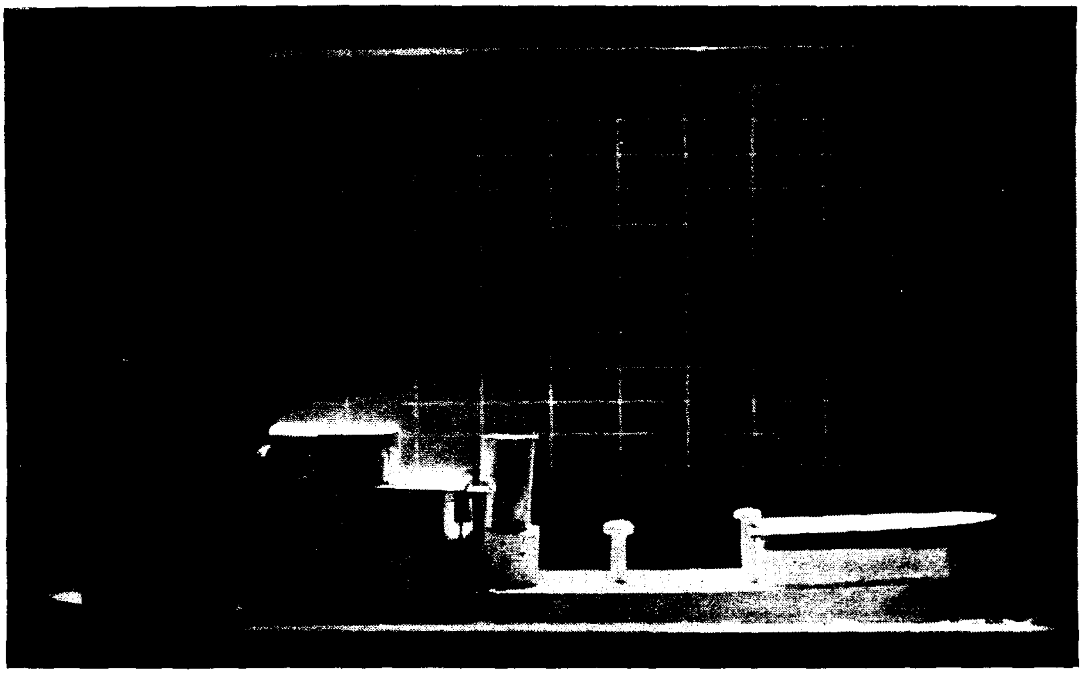


FIG. 4—LINES OF FLOW AND REGIONS OF EDDYING

(*c*) by orifice plates of various diameters, situated before the fan, in conjunction with vertical water manometers. The diameter of the particular orifice fitted depends upon the velocity range being investigated.

The most convenient way of simulating the smoke plume or making visible the gas flow was found to be by discharging saturated steam from the funnel. This steam is generated at an accurately controlled rate by electric elements in a small boiler, the flow being regulated by adjustable resistances in the element circuit. For the highest efflux velocities the steam flow is augmented by compressed air.

The velocity of efflux from the funnel is measured by a pitot tube connected to a Krell type inclined manometer. Steam and air velocities, or smoke and wind speeds, of up to 35 ft/sec can be obtained. This is considered generally to be adequate for the type of investigation.

Some Experimental Results

An instructive series of tests was carried out to show the practical independence of the effect of the S/V ratio on the absolute values of the smoke and wind speeds.

The effect of an S/V ratio of 2, with absolute velocities of 5, 10, and 15 ft/sec for the smoke, and $2\frac{1}{2}$, 5, and $7\frac{1}{2}$ ft/sec for the wind was determined. It was found that the shape of the three smoke plumes was the same in each case, despite the fact that the velocities in the third case were three times those in the first case.

It is allowable, therefore, to perform tests at any convenient smoke and wind speeds, provided that the S/V ratios are correct. This simplifies experimental procedure.

FIG. 6 (a) to (e) shows the effect of varying S/V ratio for a case in which the funnel top appears to be below the turbulence boundary. The gases are discharged into the region of intense eddies and are rapidly diffused.

For every ship, it is possible to draw a curve relating the S/V ratio to the angle of descent of the bottom boundary of the plume. For this particular case the

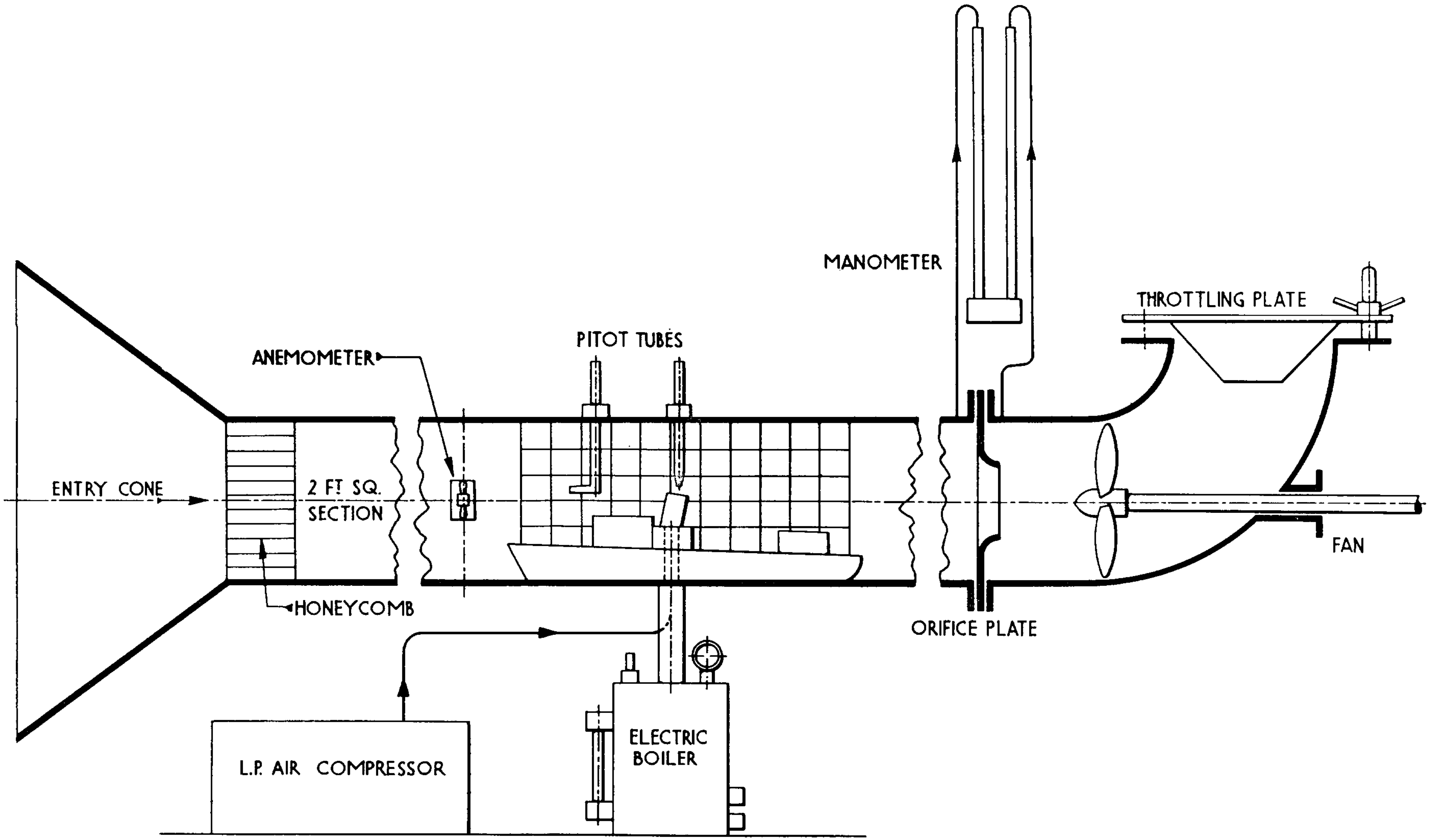
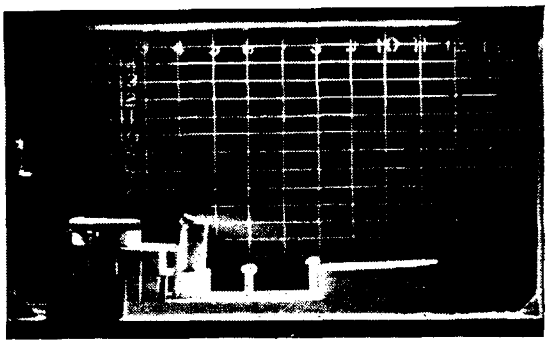
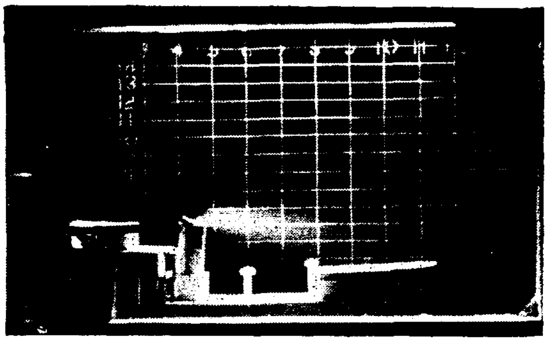


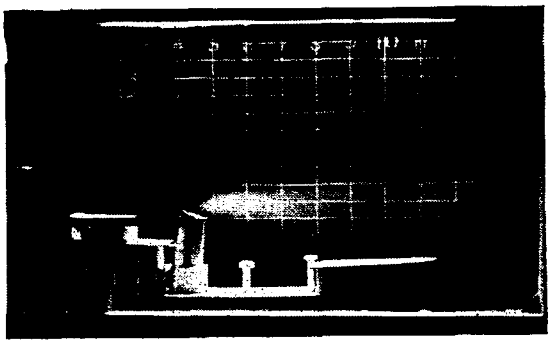
FIG. 5—DIAGRAMMATIC ARRANGEMENT OF 25-FT LOW SPEED WIND TUNNEL



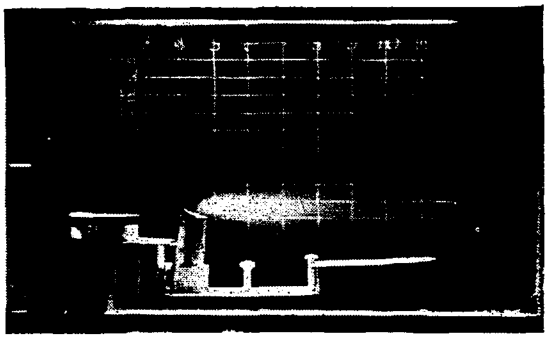
(*a*) S = 15 FT/SEC S/V = 1
V = 15 FT/SEC



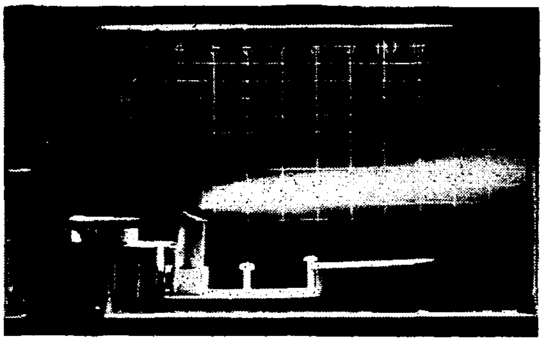
(*b*) S = 15 FT/SEC S/V = 2
V = $7\frac{1}{2}$ FT/SEC



(*c*) S = 15 FT/SEC S/V = 3
V = 5 FT/SEC



(*d*) S = 15 FT/SEC S/V = 4
V = $3\frac{3}{4}$ FT/SEC



(*e*) S = 15 FT/SEC S/V = 5
V = 3 FT/SEC

FIG. 6—THE DESCENT OF FUNNEL GASES AT VARYING S/V RATIO

curve is shown in FIG. 7—curve A. It will be seen that a horizontal bottom boundary to the plume would not be achieved until the S/V ratio approached 7.

Since the funnel gas velocity at full power in the original vessel was about 10ft/sec, this showed that the smoke plume would not be carried completely clear if the relative wind exceeded about 2 ft/sec. Since this low relative wind velocity seldom exists, there is a clear case for raising the funnel top above the turbulence boundary, increasing the efflux velocity to carry the gases through the turbulence boundary, or a combination of the two possibilities.

FIG. 8 (a) to (e) shows the same model with the same smoke and air velocities and S/V ratios but with the funnel top raised the scale equivalent of 5 feet. This appears to have brought the funnel top above the turbulence boundary. In comparison with FIG. 6 there is seen to be considerably less diffusion at the lowest S/V ratios and from FIG. 7—Curve B the bottom boundary of the plume is seen to become horizontal at an S/V ratio of about $4\frac{1}{2}$.

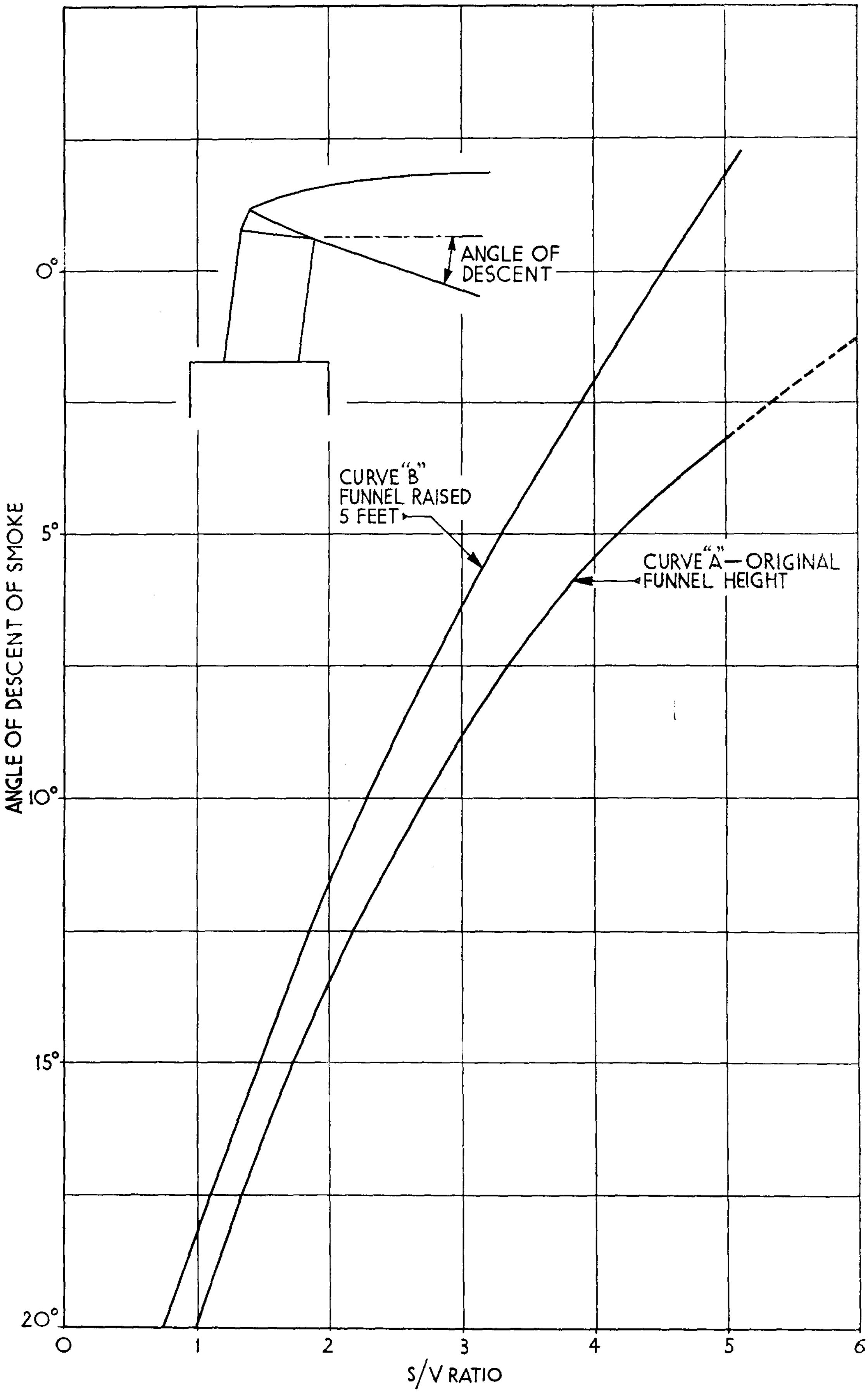
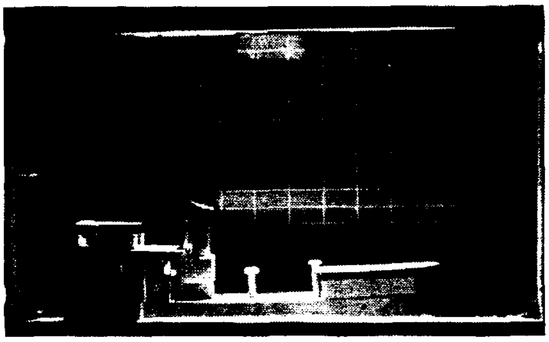
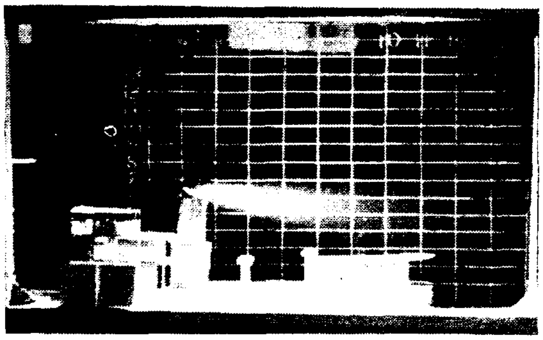


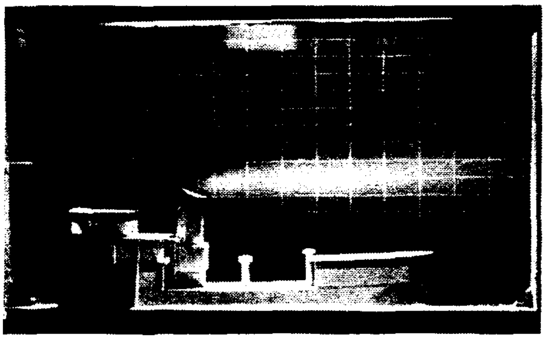
FIG. 7—CURVE OF ANGLE OF DESCENT AGAINST S/V RATIO



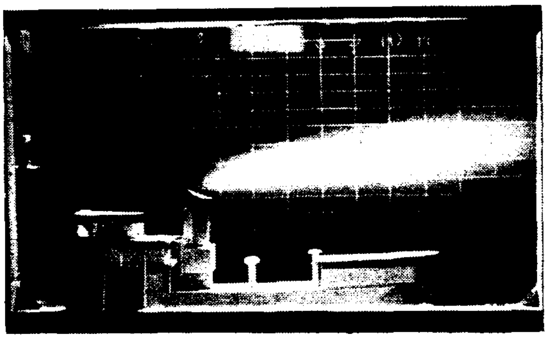
(*a*) S = 15 FT/SEC S/V = 1
V = 15 FT/SEC



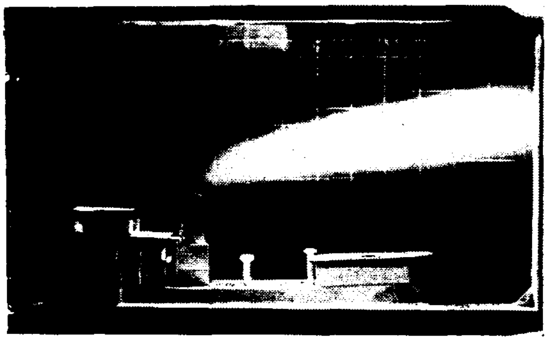
(*b*) S = 15 FT/SEC S/V = 2
V = $7\frac{1}{2}$ FT/SEC



(*c*) S = 15 FT/SEC S/V = 3
V = 5 FT/SEC



(*d*) S = 15 FT/SEC S/V = 4
V = $3\frac{3}{4}$ FT/SEC



(*e*) S = 15 FT/SEC S/V = 5
V = 3 FT/SEC

FIG. 8—THE PATH OF FUNNEL GASES AT VARYING S/V RATIO WITH FUNNEL RAISED 5 FEET

Since it is hardly possible, from considerations of topweight and appearance, to increase the funnel height by more than about 5 feet for this particular vessel, we are led to consider the possibility of increasing the momentum of the funnel gases. Two possible methods of doing this will be considered later ; both involve the expenditure of mechanical work. The extent to which the height of the funnel can be increased is shown by those of the *Liberté* (formerly *Europa*). These funnels originally were only 31 feet high. After a short period of service their height was increased to 47 feet. When the ship came under French ownership the funnels were raised to a height of 60 feet—practically twice the original height.

The Shape of the Funnel

We shall consider now the influence of funnel shape, as opposed to height.

The ‘ drawdown ’ effect on a freestanding cylindrical funnel has been shown in FIG. 1. The effect would not be so pronounced on the cylindrical funnel

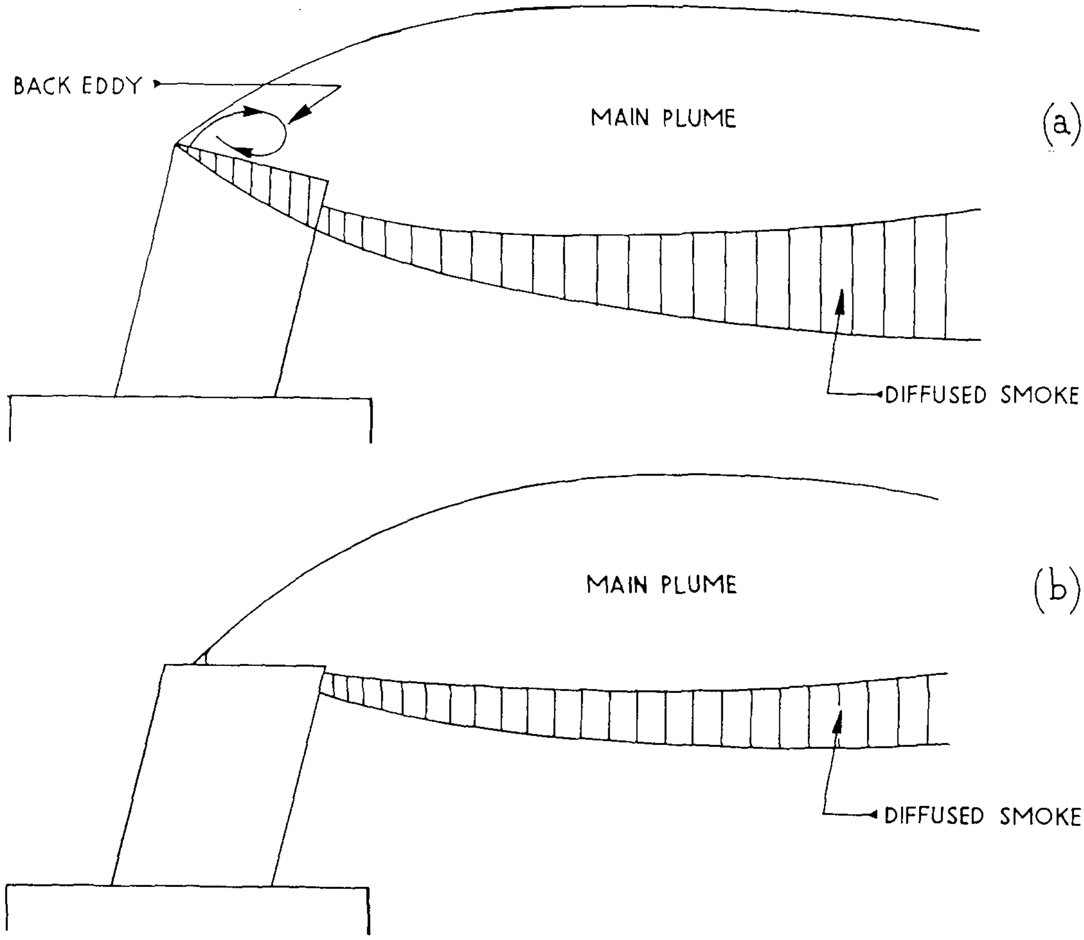


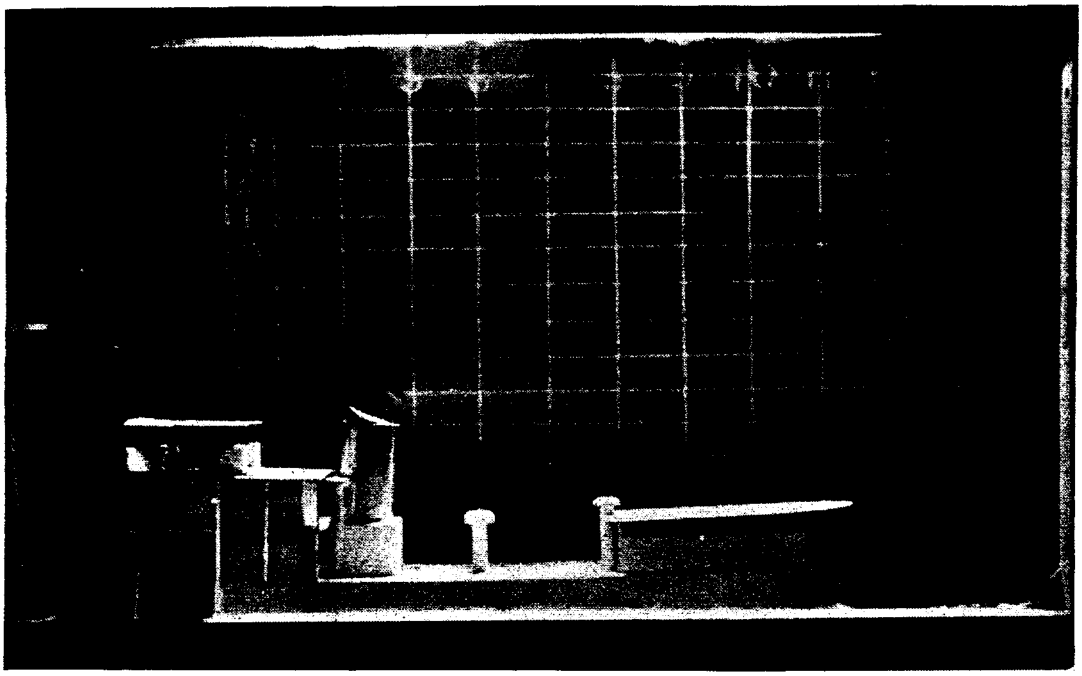
FIG. 9—EFFECT OF RAKED AND NON-RAKED FUNNEL TOP

standing in the wake of a superstructure, since the resultant eddies around the funnel tend to counteract the reduction in pressure in its rear due to its cylindrical form. Nevertheless, there remains a drawdown which may amount to two or three funnel diameters. The effect of the drawdown is to precipitate solids from the funnel gases on to the decks around the funnel.

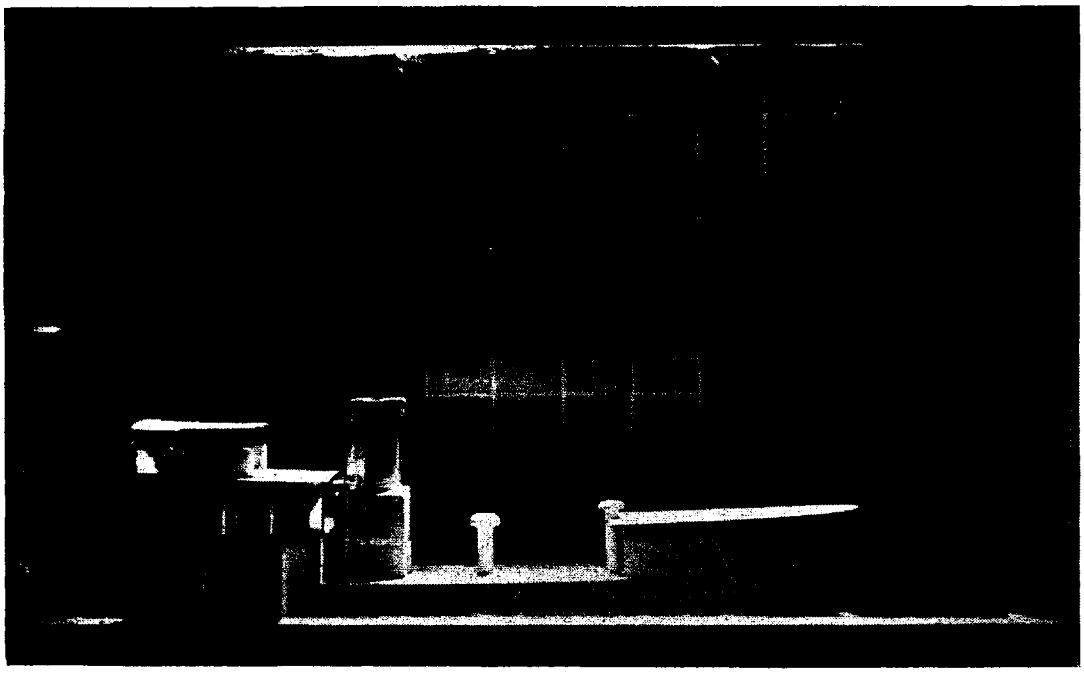
The effect of a streamlined outer casing has been shown in FIG. 2 (a), (b), and (c) for funnel sections having thickness/chord ratios decreasing from 0·56 to 0·31. The drawdown is very materially reduced, with a consequent reduction in the quantity of solids deposited around the funnel. It appears that a thickness/chord ratio of about $\frac{1}{3}$ is adequate.

The shape of the top of the funnel has a considerable effect on the shape of the plume. The effect of a raked top, or of a cowl on the forward lip of the funnel giving the effect of rake, is bad. An eddy is caused at the forward lip of the funnel and diffused smoke is washed down the sides of the funnel as shown in FIG. 9 (a).

The effect of making the top of the funnel parallel to the water line is to reduce the amount of diffused smoke considerably as shown in FIG. 9 (b). The photographs of FIG. 10 (a) and (b) illustrate the effect for an S/V ratio of 2. The reduction in diffused smoke is noticeable particularly for low S/V ratios. A flat annular plate or rim at the after lip of the funnel has been found to reduce the drawdown.



(*a*)



(*b*)

FIG 10—PHOTOGRAPHS AT S/V = 2 SHOWING BENEFICIAL EFFECT OF NON-RAKED FUNNEL TOP

In recent years a number of aerodynamic devices for funnels have been patented. Most of these employ slots or ducts in the outer casing designed to deflect the airstream into the vertical direction and to increase its velocity. Since these ducts and slots offer appreciable resistance to free flow, most of the air will take the path of least resistance round the outside of the casing. The writer has yet to see convincing demonstrations of the effectiveness of this class of apparatus.

The Aerofoil Funnel

An interesting exception to this class of funnel is that developed by Valensi and Guillonde, which is the subject of French Patent No. 537,822. This is described in the papers listed below.

In side elevation the funnel is in the form of half an aircraft wing and in section has the shape of a symmetrical aerofoil with a thickness/chord ratio of not more than $\frac{1}{5}$. It is known that the wing-tip vortex of an aerofoil is constituted, very approximately, by a cylindrical core with its axis parallel to the relative wind. Around this core, the diameter of which is about 1/10th of the wing chord, the air twists spirally, making a practically cylindrical surface of a diameter equal to about half the chord. The funnel aperture is positioned so that the gases are emitted into the core of the wing-tip vortex, one of the chief characteristics of which is that it retains its individuality for a considerable distance downstream.

The authors carried out tests in the wind tunnel at the Institut de Méchanique des Fluides de Marseille, and at sea. These confirmed that, for the particular ship examined, where the funnel just penetrated the turbulence boundary, the smoke was carried clear of the deck for relative winds from 0° to 30° incidence.

Deflector Plates

It might be supposed that by imparting an upward component to the relative wind by means of deflector plates placed forward of the funnel, the smoke could be carried clear of the decks. Admiralty experiments at sea have shown that, in certain cases, such deflector plates are effective. The deflectors require to be equal in span to the funnel width with a chord of about $\frac{1}{3}$, fitted at a height not less than that of the turbulent boundary.

In other cases, where the superstructure is particularly high and bluff, such deflector plates are ineffective. In a particular instance investigated by the writer, the deflector plates, to be effective, would have had to be of great size and fitted about 10 feet above the highest part of the superstructure. This would be impracticable from considerations of appearance, weight, and stability.

Efflux Velocity of the Funnel Gases

We now consider the two methods, previously mentioned, of increasing the momentum of the funnel gases. They are :—

(*a*) by increasing the forced draught pressure,

(*b*) by blowing additional air out of an annulus surrounding the inner funnel, in the form of a high-speed sheath.

(*a*) *Increase in Forced Draught Pressure*

In the past, the funnel gas efflux velocities of merchant ships have varied from 10 to 20 ft/sec at full power, with the majority at the lower end of that range. These velocities seem to have been established as standard in the days of tall funnels and natural draught. With forced draught systems, the only limitation is the amount of extra forced draught fan power which the marine engineer is willing to accept. In America, funnel gas velocities of 150 ft/sec are being considered and in H.M. Yacht *Britannia* a velocity of 110 ft/sec is attained at full power.

In passenger vessels it may well be false economy to restrict the funnel gas efflux velocity to that acceptable from the thermodynamic considerations of specific fuel consumption.

(*b*) *High-Velocity Air Sheaths*

A most effective method of preventing the descent of funnel gases is to surround the discharging gases with an annular high-velocity air jet. The air, which may be obtained from machinery space ventilation exhausts or may be drawn from the atmosphere, is discharged through an annulus of appropriate size formed between the inner and outer funnel casings. The high-speed air sheath acts as an isolating belt which prevents the funnel gases from being drawn into the low pressure zone behind the funnel, and, above all, it is effective at all powers.

Tests in the wind tunnels at the National Physical Laboratory and at the State School of Engineering at Kiel have demonstrated the effectiveness of this method. The use of a high velocity air sheath has also been investigated extensively by the United States Maritime Commission.

The model tests suggest that the volume of air discharged through the sheath should approach that of the funnel gases and the velocity of discharge through the annulus should be at least equal to that of the relative wind. American sources suggest that velocities of from 60 to 130 ft/sec may be required. Again, the fitting of this considerable apparatus may be justified in an otherwise smoke-polluted passenger ship.

The Funnel of H.M.Y. ' Britannia '

As an example of the latest practice under particularly stringent conditions we may consider the funnel of H.M. Yacht *Britannia.* The requirements were, of course, that the funnel should have a pleasing appearance, that the decks should be free from smoke and gases, and that the paint-work should not be discoloured by smoke and gases eddying in the vicinity.

The size and shape of the funnel were decided with the assistance of the National Physical Laboratory, who conducted wind tunnel tests on various funnel designs for the Admiralty. As was to be expected, the most efficient funnel suggested by the wind tunnel tests was not acceptable because of its height and the shape of its top.

FIG. 11, which is taken from Sir Victor Shepheard's paper on the Royal Yacht, shows the funnel as first tested (A), and as finally fitted (B).

With funnel A considerable eddying occurred and extended down the sides of the funnel to the superstructure level. In funnel B the section was given a more streamlined shape with a better aerodynamic form substituted for the semicircular front. The top of funnel B is cased in. With these changes there was a great improvement in funnel performance, and further improvement was obtained by grouping the uptakes instead of distributing them over the funnel top. Grit arresters are fitted in the uptakes.

In view of the previous remarks in this article on current funnel efflux velocities in British ships, it is of particular interest to note that a major factor in producing a clean Royal Yacht, according to Sir Victor Shepheard, is the high efflux velocity of the funnel gases at all powers. Efflux velocities vary between 110 ft/sec at 12,000 s.h.p. and 80 ft/sec at 1,000 s.h.p.

It is hardly surprising, therefore, that the many ships with efflux velocities in the 10 to 15 ft/sec range and with funnel tops below the turbulence boundary should carry with them a pall of smoke, smuts, and combustion gases.

Conclusions

Complete elimination of trouble due to the descent of smoke, soot, and gases to the decks is probably impossible, at least with the funnel heights at present

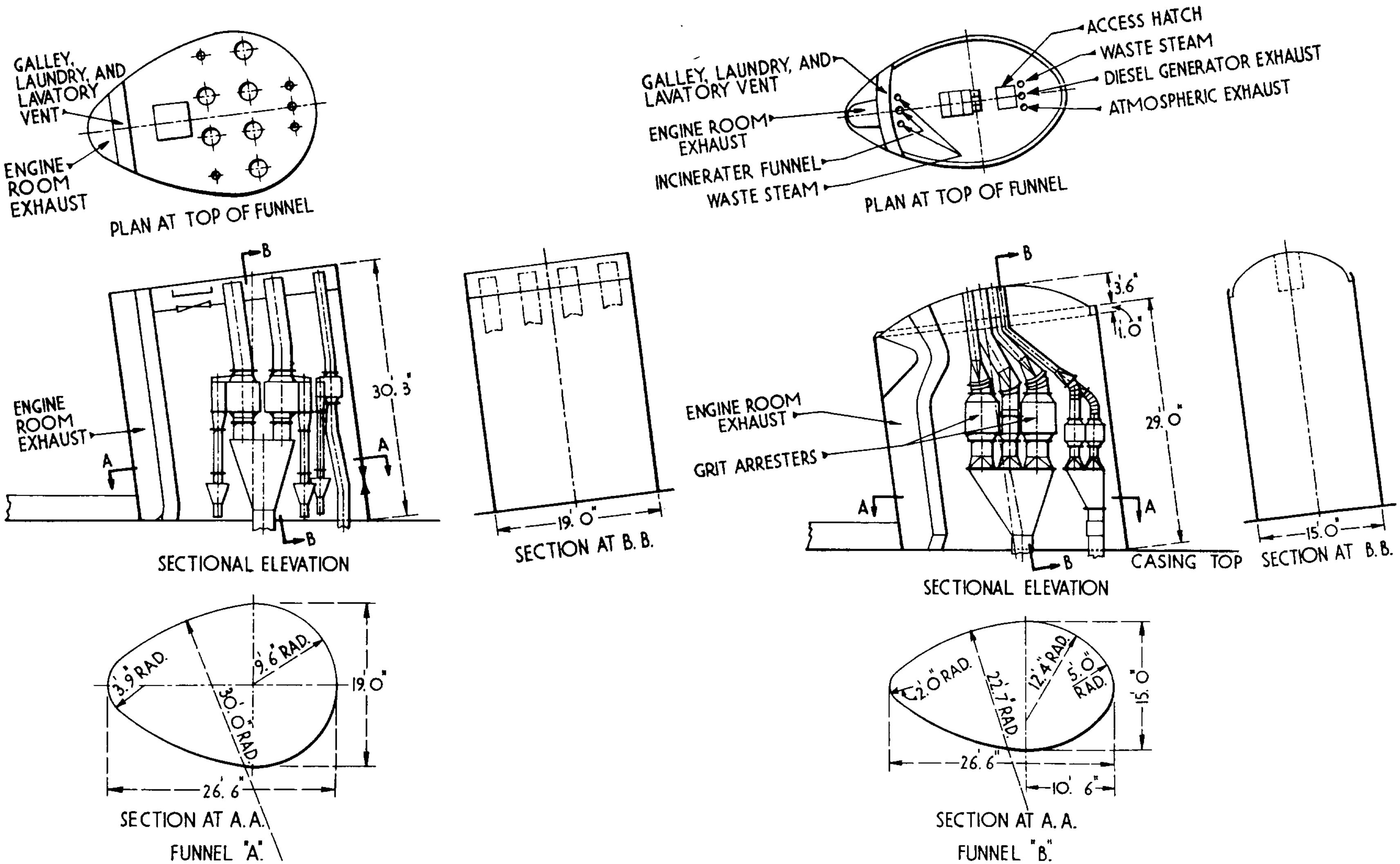


FIG. 11—H.M. YACHT 'BRITANNIA' FUNNEL DESIGN

acceptable. The amount of smoke pollution which can be accepted will vary from one type of ship to another. The requirement is most stringent, obviously, for the large passenger liner. The designers and owners must decide in each case what price they are prepared to pay in appearance and running costs for an approach to a smoke-free ship. If, as in the new Shaw Savill liner *Southern Cross*, the machinery is aft, the problem becomes very much simpler.

For conventional layouts, however, the following conclusions can be drawn. Some recommendations are obvious, yet are often neglected.

(*a*) The funnel should be as high as possible—at least high enough to project for one diameter through the turbulent boundary.

(*b*) The funnel gas efflux velocity should be as great as possible, a balance being drawn between good habitability and thermal economy for each class of ship.

(*c*) The uptakes should be grouped together at the funnel top and the unused area covered in by a streamlined casing. The diameter of the funnel top should be made as small as possible ; it is here that the conflict between the aesthetic and the expedient is most acute.

(*d*) The cross section of the outer funnel casing should be given a good streamlined form. An aerofoil section with a thickness/chord ratio not greater than $\frac{1}{3}$ is indicated.

(*e*) The top of the funnel should not be raked, but should be parallel to the waterline. A flat annular plate surrounding the top of the funnel is an advantage.

(*f*) At present, the surest method of eliminating smoke pollution is to fit a high-velocity air sheath. This appears to be effective at all powers and any direction of the relative wind. The initial and running costs, however, may restrict its application to special cases.

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