the pressure is increased, resulting in an elevation of the surface of the water at those places. A wave is thus formed at the bow and stern, requiring an expenditure of energy for its maintenance and entailing additional resistance.

Of these components of resistance, that due to eddy making is usually small; eddying is caused by blunt beginnings or endings, particularly the latter, in the water-lines and underwater fittings. Air resistance also is generally of small importance; in the “ Grey­hound ” (unrigged) it constituted 1∙4% of the total resistance at 10 knots in calm weather, and in a large Atlantic liner at 25 knots it absorbs about 4% of the total power. In the case of average ships, unrigged or with moderate top-hamper, the proportion of air resistance is probably less than the latter value. The effect of wind and rough weather on the speed of ships is also largely due to the action of the waves and other motion of the sea, the additional effect of which is indeterminate.

The difference between the total resistance and that due to skin friction is termed the residuary resistance ; from the foregoing remarks it appears that it consists principally of the resistance due to wave- making. Since the action of the waves is such as to distort the stream lines near the hull, and the form of the waves is in turn affected by the frictional wake, the frictional and wave-making resistances of a ship are to some extent mutually dependent. It is convenient, however, to neglect the interaction of these constituents, and to assume that the whole resistance is obtained by simple summation of its component parts as calculated independently. Considerable justification for this assumption is furnished by the close agreement between the results of experiments on models and on ships, where the proportion of factional to total resistance is greatly different.

propeller to be removed, and the ship to be towed through undisturbed water. Under these conditions the power expended in towing the vessel is termed the *effective horse power,* and is considerably less than the indicated horse power exerted by the propelling engines at the same speed. The relation between the effective and indicated horse powers, and the effect of the propellers on the resistance of the ship will be discussed under *Propulsion,* below.

If a body of “ fair ” form, *i.e.* without abruptness or discontinuity in its surface, moves uniformly at a considerable depth below the surface of an incompressible and perfect fluid, it can be shown that no resistance is experienced, and the uniform motion will*, caeteris paribus,* continue indefinitely. The motion of the fluid is extremely small, except in the close vicinity of the body. A clearer conception of the interaction of fluid and body is obtained by impressing upon the whole system a velocity equal and opposite to that of the body, which then becomes motionless and is situated in a uniform stream of the fluid. The particles of fluid move in a series of lines termed “stream lines”; and the surface formed by all the stream lines passing through a small closed contour is termed a stream tube.” If *a* denote the area of a stream tube, assumed sufficiently small for the velocity *ν* at a point within it to be sensibly uniform across a section, then, since no fluid is leaving or entering the tube,

*a.v=* constant throughout its length. The motion of the fluid is also subject to Bernoulli's energy quotation—

^+^+Λ=constant,

*p, w* and *h* being respectively the fluid pressure, the density and the height above a fixed datum.

The remaining conditions affecting the flow and determining the forms of the stream lines are purely geometrical, and depend on the form of the body.

The motion in a perfect fluid flowing past bodies of a few simple mathematical forms has been investigated with success, but in the general case the forms of the stream lines can only be obtained by approximate methods. It is evident that the flow is in all cases reversible since the equations are unaltered when the sign of *v* is changed; on the other hand any resistance must always oppose the motion, and therefore, as stated above, there can be no resistance under these conditions.

The circumstances attending the motion of a ship on the surface of the sea (or that of a stream of water flowing past a stationary vessel) differ from those hitherto assumed; and resistance is exρcri- enced through various causes.

Frictional resistance results from the rubbing of the water past the surface of the hull; eddy resistances are caused by local discon- tinuities, such as shaft brackets; and resistance due to wind is experienced on the hull and upper works. Moreover, the stream-line motion, as will be shown later, causes a diminution in the relative velocity of the water at the ends of the ship; from the energy equation above, it is evident that

Since the action and the reaction of the water pressure on the hull of a ship are equal and opposite, forward momentum is generated in the water at such a rate that the increase of momentum per second is equal to the total resistance. The water participating in the forward movement is termed the *wake* ; the portion of the wake in the vicinity of the propellers is found to have considerable effect upon the propulsion of the ship. Experiments were made by Mr Calvert *(Trans. Inst. N.A.* 1893) to determine the wake velocity with a model of length 28½ ft. and displacement 2∙9 tons. The extent of the wake was measured at various positions in the length, and its maximum velocity was observed to be 0·67 times the speed of the ship. Abreast the screw the mean velocity ratio over an area of the same breadth (3∙66 ft.) as the ship and of depth equal to the draught (1∙55 ft.) was 0∙19, of which about 0∙05 was ascribed to frictional resistance. In *Rep. Brit. Assoc.* 1874 is contained an investigation by Fronde of the extent of the frictional wake and its velocity distribution based on the equality of the resistance to the momentum added per second. It may be here observed that for any ship propelled in the ordinary manner at uniform speed the momentum generated in the sternward race from the propeller is equal and opposite to that of the forward wake due to the hull. The motion of the water as a whole thus consists of a circulatory disturbance advancing with the ship, and having no linear momentum.

The whole of the resistance at low speeds, and a considerable proportion of it at higher speeds, is due to surface friction, *i.e.* to the eddying belt surrounding the hull which is caused by the tangential frictional action between the water and the outside skin. It is nearly independent of the form of the vessel;

and is conveniently estimated from the results of experiments made by towing in a tank planks coated with various surfaces. The most important of such experiments were those made by Froude in the experimental tank at Chelston Cross, Torquay. The object was to obtain the laws of variation of resistance with the speed, the length, and the quality of the surface. A dynamometric apparatus by which the planks were towed was used to register the resistance; the planks were given a fine edge at each end to avoid eddy making, and were fully immersed in order that no waves should be formed. The results are given in the *Reports of the British Association,* 1872 and 1874. In the following extract *n* is the index of the speed at which the resistance varies, A the mean resistance per square foot of surface over the length stated, and B the resistance per square foot at the after end of the plank; both A and B refer to a velocity of 10 ft. per second in fresh water.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Length of Surface in Feet.* | | | | | | | | | | | | |
|  | 2 ft. | | | 8 ft. | | | 20 ft. | | | 50 ft. | | |
| n. | A. | B. | ***η.*** | A. | B. | n. | A. | B. | *n.* | A. | B. |
| Tinfoil . | 2∙16 | •30 | ·295 | 1·99 | •278 | •263 | 1∙9o | ·262 | \*244 | 1∙83 | •246 | •232 |
| Paraffin | 1·95 | ·38 | ·370 | 1∙94 | ·314 | ·260 | 1·93 | ·271 | \*237 |  |  |
| Varnish | 2∙00 |  | ·390 | 1∙85 | ·325 | •264 | 1∙85 | ∙278 | ·240 | ι⅛ | \*250 | •226 |
| Fine sand . | 2-00 | •81 | •690 | 2’00 | •583 | •450 | 2-00 | ’48O | '384 | 2∙o6 | •405 | ’337 |
| Calico .  Medium sand . | .ι∙93 | ‘ ∙87 | \*725 | 1∙92 | •626 | •504 | 1’89 | •SSI | •447 | p87 | •474 | •423 |
| 2-00 | •90 | •730 | 2∙oo | •625 | •488 | 2∙oθ | •534 | '465 | 2-00 | •488 | •456 |
| Coarse sand | 2-00 | I·IO | •880 | 2-00 | •714 | ∙52o | 2∙∞ | •588 | \*490 | . · | . ► |  |

These results are in accordance with the formula—

Vλ

R=>S∙⅜ι

R being the frictional resistance, S the area of surface, V the speed, *w* the density of the water, *f* a coefficient depending on the nature and length of the surface, and *n* the index of the speed ; the values of *f* and *n* can be readily obtained from the above table. It is seen that the resistance varies as the density of the water, but is independent of its pressure; it diminishes as the length of the surface increases, on account of the frictional wake, which reduces the velocity of rubbing between the water and the surface towards the after end. The index *n* is 1∙83 for a varnished surface equivalent to the freshly painted hull of a ship. The results of Froude’s ex­periments are closely corroborated by similar experiments under- taken by the late Dr Tideman..

When applying the data to ships of length greater than 50 ft., the coefficient B, denoting the resistance 50 ft. from the bow, is assumed to remain unaltered at all greater distances astern. The velocity of rubbing is assumed equal to the speed of the ship, any slight variation due to stream-line action being neglected. The wetted surface S, when not directly calculated, can be estimated with sufficient accuracy by the formula—

s=1∙7LD+p

where V is the volume of displacement, L the length, and D the mean draught.

The resistance due to wave making, although inconsiderable at low speeds, is of importance at moderate and at high speeds; it constitutes the greater portion 01 the total resistance in fast ships.