MARINE DIESEL POWER PLANTS and Ship Propulsion

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THE revolutions per minute of marine propellers is determined by hydrodynamic considerations. The type of engine furnishing the propeller with the necessary power does not affect the speed for best propeller efficiency. It is the engine designer's task to provide the propeller with the power and speed required by the naval architect. Besides, the power plant is to weigh as little as possible and to take up a minimum of space in the vessel.

In order to obtain an idea of the order of magnitude of the speed for maximum propeller efficiency as affected by forward speed and shaft horsepower, average values for a series of commercial vessels have been collected and plotted. A plot of such data is shown in Fig. No. 1. It is seen that the required propeller speed becomes quite low, especially at low speeds and large power. If the engine is directly coupled to the propeller shaft, the engine size will be excessive, unless the power is subdivided into two engines and propellers. A definition of propeller efficiency and its relation to ship propulsion is given in the appendix. Since the initial cost of an installation is proportional to its weight, direct drive with low engine speed will be both heavy and expensive.

DIRECT AND GEARED DRIVE

The difficulty of direct drive described above has led to the application of gear transmissions to marine Diesel drives. This allows the propeller to operate at its best rate of speed without imposing limitations on the engine speed. It furthermore permits the subdivision of the engine into several independent units, all geared to the same shaft through the transmission. It is usual to gear two parallel engines to one propeller shaft. However, there are installations which have four engines driving a single shaft. The gear transmission enables the engine speed to be selected within wide limits. As a result of high engine speed a considerable gain in weight and space is obtained. The cost of the installation is decreased in proportion to the decrease in weight.

To illustrate the saving in weight and space for a given vessel, Fig. No. 2 shows sections of a cargo vessel with a displacement of 8,000 tons and 2,500 shaft-horsepower (*shp*). Installation *A* represents a direct drive Diesel engine. Propeller and engine speed are equal (80 revolutions per minute). The weight of the installation is 242 pounds per shaft-horsepower. Installation *B* shows two parallel engines geared to the propeller shaft through a transmission. Propeller speed is 80 revolutions per minute, as before, and the engines are running at 250 revolutions per minute. Weight of the twin engine installation is 116 pounds per shaft-horsepower. The saving in weight and space is appreciable.

In common Diesel engine terminology such an installation would be called a high speed installation. It should be kept in mind that this term is applied to any Diesel engine running at or above about 250 revolutions per minute.

As mentioned above, direct drive limits the number of engines to the number of the propeller shafts. An example will illustrate the effect of this limitation on cruising economy: A given vessel is designed to run at 15 knots at rated full power. Cruising speed, at which most of the operation will be maintained, is 11 knots (i.e., 73 per cent of full speed). For this speed, only 40 per cent of rated full power is required. Fig. No. 3 shows a curve of specific fuel consumption for a typical two-stroke marine Diesel engine plotted against load. The consumption at full power is 0.361 pounds of fuel per brake power hour. At 40 per

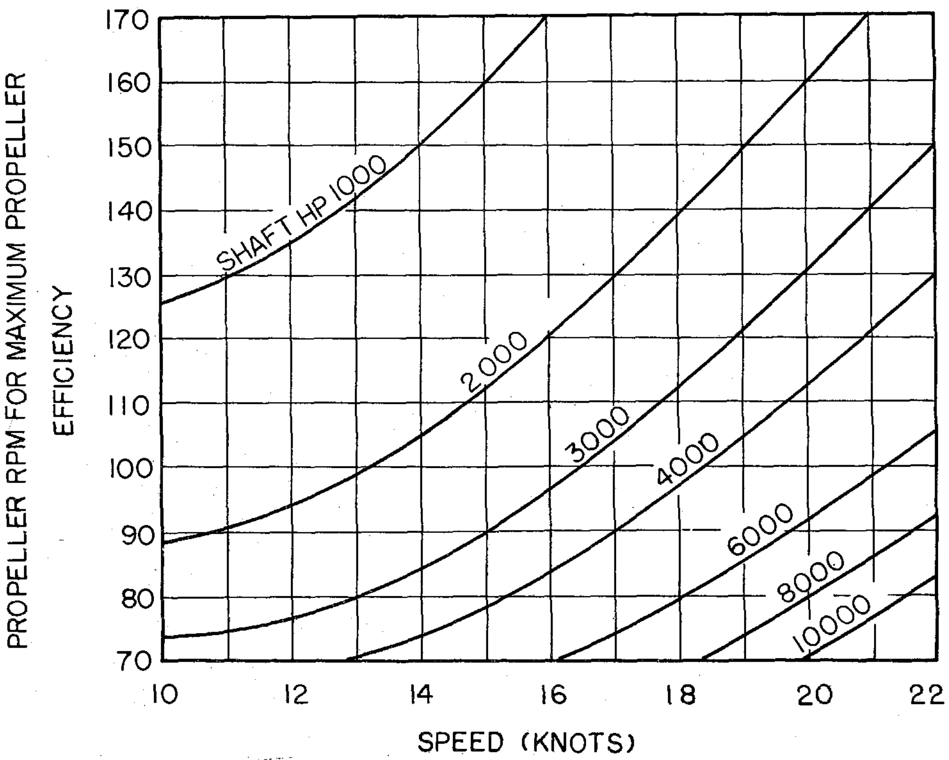

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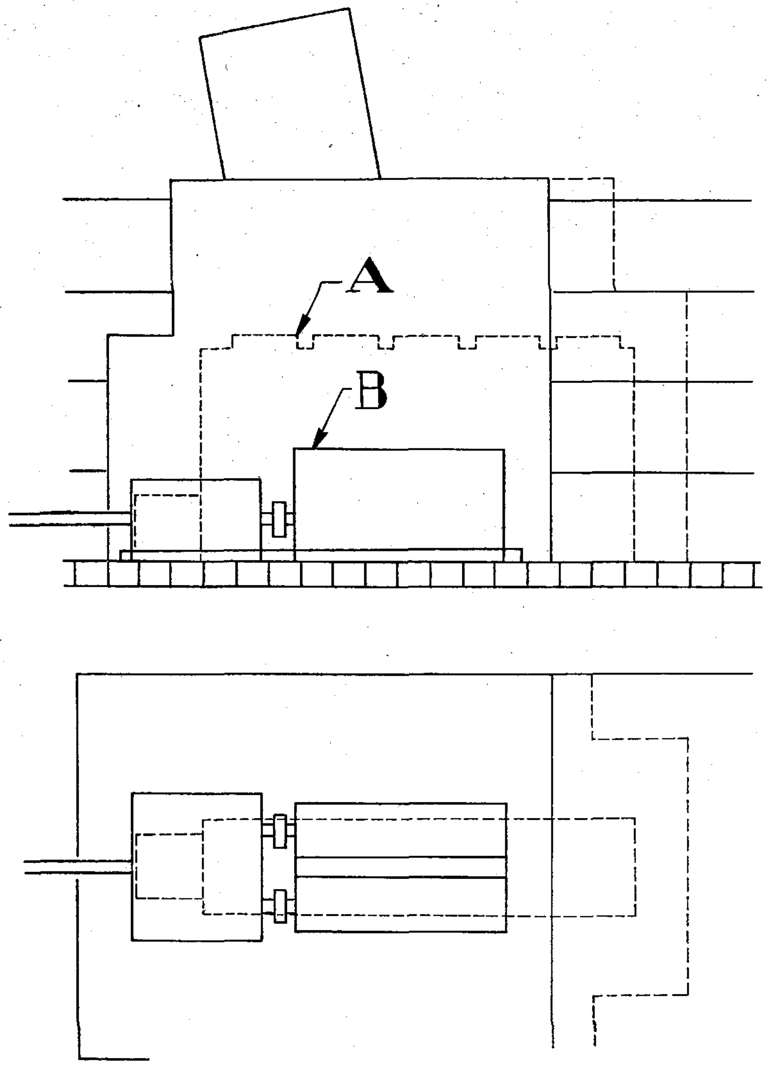
FIG. 1—Propeller revolutions per minute for maximum propeller efficiency vs. speed for different shaft horsepower.



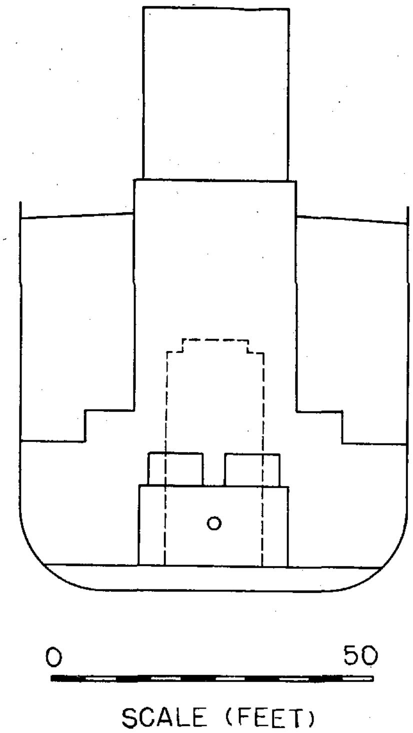


FIG. 2—Space required for direct drive (A) and geared (B) diesel engine installation. 8000-ton freighter with 2500 shaft horsepower at 80 propeller revolutions per minute.

cent power it is 0.361 pounds of fuel per brake power hour. The geared twin engine drive would reduce power for cruising by disengaging one engine completely. The remaining engine would then run at 80 per cent of its full power with a specific fuel consumption of 0.349 pounds of fuel per brake power hour. It has been assumed in this example that the variation of fuel consumption with load is the same for the individual engine of the twin installation and for the single engine of twice the power. This is not necessarily true. However, for engines above a certain power this assumption is permissible.

The twin-engine drive also adds to the safety of operation. In case of failure of one engine, the trip can be continued on the functioning engine. Often, repairs can be made during the trip, thus materially reducing the period for which the vessel is tied up for overhaul.

A NOTE ON RATED ENGINE POWER

In connection with Fig. No. 3 a remark about rated engine power is in order. It will be noticed that the curve of specific fuel consumption has not yet reached its minimum value at 4/4 load, that is, at full rated power. For the engine from which Fig. No. 3 was taken, the rated full power was 3,750 brake power. 110 per cent overload, or 4,125 brake power were listed as allowable continuous overload. The maximum power obtained in the acceptance test was 5,300 brake power, or 141 per cent of rated power. This represents a case of conservative rating. It is clear that such a rating lets the engine show up poorly as far as weight per horsepower is concerned. From a point of view of maintenance and engine life, however, the practice of

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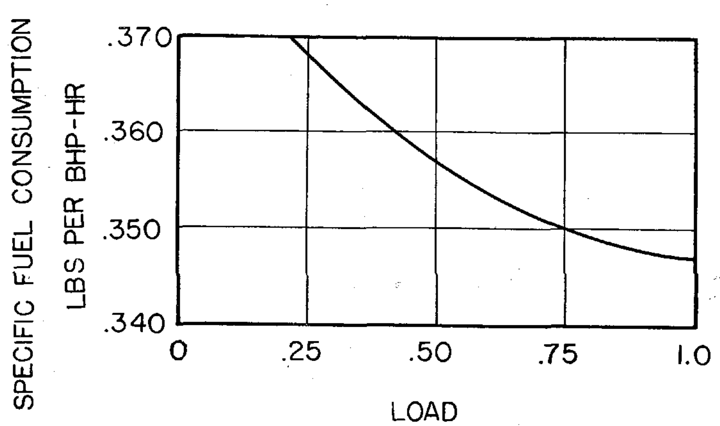
FIG. 3 — Specific fuel consumption of a typical marine diesel engine (4000 brake horsepower two-stroke).



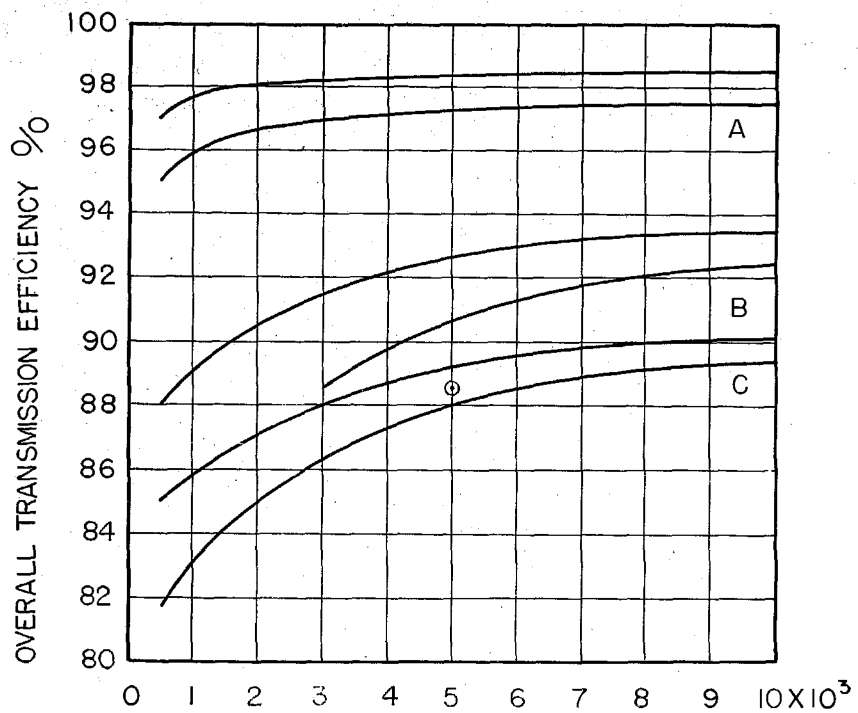


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FIG. 4—Transmission efficiency vs. shaft horsepower for different types of power transmission. Curves (A): Gear transmission; Curves (B): Electric transmission (A.C.); Curves (C): Electric transmission (D.C.). (The circle indicates a point for diesel-electric drive from Fig. No. 5).

conservative rating, sometimes called "rating down," pays by reducing engine wear and failure due to overload. Manufacturers are inclined to present maximum powers in order to make them compare favorably with other power plants.

In a similar fashion, weight figures are often optimistic, since they are based on an arbitrary list of parts assumed to constitute an engine.

TWO- AND FOUR-STROKE ENGINES

For a given power and speed, weight and space required of the power plant will also depend on the type of engine chosen. To illustrate this, Table No. I shows a comparison of three engines having the same power and speed. Engine *A* is a single acting two-stroke engine, *B* a four-stroke engine with exhaust turbo supercharger, *C* an unsupercharged four-stroke engine.

It is seen that the two-stroke engine is both lighter and more compact than the two other types, a reason why two-stroke engines have gained in popularity during recent years. The advent of exhaust turbo supercharging has again put two- and four-stroke engines side by side, at least as far as weight is concerned. The exhaust supercharged four-stroke engine is seen to be only 7.3 per cent heavier than the two-stroke engine, and slightly larger in size. The unsupercharged engine is 25 per cent heavier than the two-stroke engine and considerably longer.

EFFICIENCY OF GEAR TRANSMISSIONS

The foregoing examples have shown the desirability of gearing an engine with relatively high speed to the propeller shaft. As a result, gear transmissions are extensively used, usually in connection with mechanical or hydraulic clutches and couplings. This form of power transmission is, of course, equally applicable to steam turbines and Diesel engines as prime movers. The transmission efficiency (see appendix for definition) of gear transmissions is high, as shown by curves *A* of Fig. No. 4. The upper curve represents single, the lower double reduction gears.

Although high, the initial cost of reduction gears is rarely a deciding factor for or against gear transmissions in comparison with electric power transmission, at least on large installations.

Considerations of safety, simplicity of design, maintenance, noise, and vibration and their evaluation as design factors are subject to personal preferences and allow no general statements.

DIESEL ELECTRIC DRIVE

Because of the twofold power transmission, the Diesel electric drive has a lower transmission efficiency than the gear drive, as shown by curves *B* of Fig. No. 4, representing A.C. installations and curves *C* for D.C.

Since Diesel fuel and fuel oil are comparative in cost and heating value, fuel consumption is a suitable basis for comparing the various Diesel drives with each other and with steam turbine drive. Table No. II shows such a comparison. It is seen that the Diesel drive has the advantage. For a 10,000 shaft-horsepower installation the fuel saving of the Diesel drive as compared with the steam turbine would be 2,200 pounds of fuel per hour. In making this comparison, it should be kept in mind that Diesel power plants are not suitable for very

TABLE I—COMPARISON OF WEIGHT AND SIZE OF DIESEL ENGINES OF DIFFERENT TYPES AND EQUAL POWER

Type of engine:	(*A*) *Two-stroke, single acting engine*	(*B*) *Four-stroke, exhaust-supercharged*	(*C*) *Four-stroke, unsuper-charged*
bhp	510	510	510
Engine rpm	350	350	364
Weight of engine (lbs.)	30,500	33,000	45,850
Weight of auxiliaries (lbs.)	4,750	5,400	5,850
Weight of coupling and transmission (1:2) (lbs.)	6,400	6,400	6,400
Weight of installation per bhp	82	88	102.5
Overall length of engine (inches)	134	153	183
Overall height of engine (inches)	92	98.5	95
Increase in weight/bhp over engine (*A*) (per cent)		7.3	25

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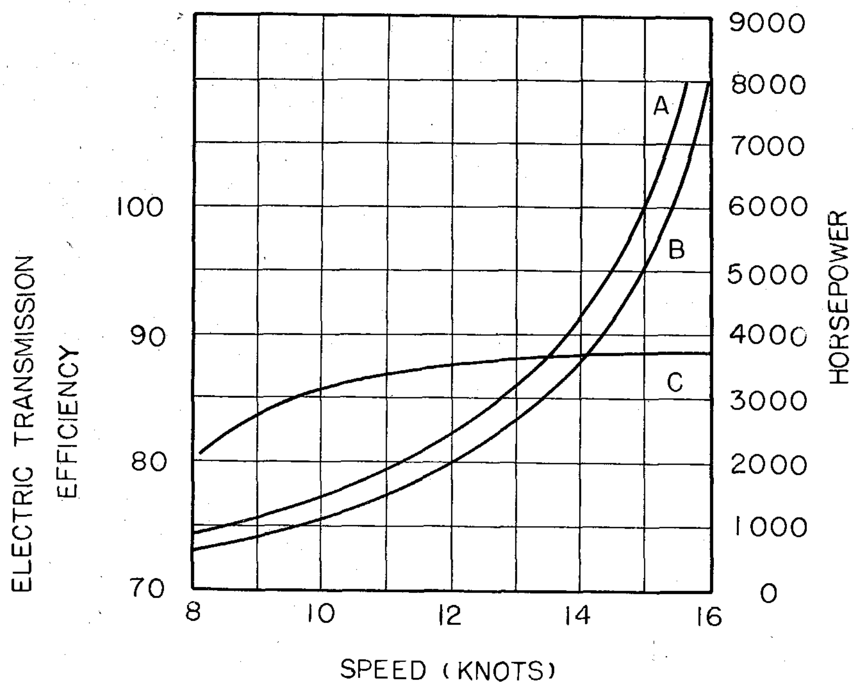
FIG. 5—Power vs. transmission efficiency vs. speed for diesel-electric (D.C.) drive of an 8000-ton ice breaker. Curve (A): Engine brake horsepower; Curve (B): Shaft horsepower; Curve (C): Transmission efficiency.



large powers. For powers above 50,000 shaft-horsepower the steam turbine is definitely the more compact installation.

Fig. No. 5 shows a plot of power and transmission efficiencies vs. speed for a Diesel electric (D.C.) installation of an ice-breaker of 4,330 tons displacement and six 1,500 brake power engines. One point of this plot at V=15 knots and 5,000 shaft-horsepower has also been plotted on Fig. No. 4 and is seen to fall well within the designated D.C. region.

A great advantage of the electrical installation is the fact that the engine-generator unit is completely independent of the propeller motor. This eliminates long shafts and shaft tunnels and numerous bearings. The designer can, therefore, dispose more freely of the space within the vessel.

Propeller rotation is reversed electrically, eliminating the necessity of reversing the main driving Diesel engine. Besides, the drive is controlled directly from the bridge.

D. C. OR A. C. DRIVE

Direct current drive is desirable because of its continuous speed control. Its disadvantage lies in a lower transmission efficiency (Fig. No. 4), greater weight and initial cost, as compared with alternating current drives. Commutators are considered an unpleasant source of maintenance difficulties, particularly in installations with large power. For these reasons, 10,000 shaft-horsepower is the upper practicable limit for D.C. installations.

A.C. drives lack the flexible speed control of D.C. installations. There is, however, no limit to the power that can be handled. Simple construction and the possibility of using high voltages are decided advantages. Use is also made of the synchronous driving motors to synchronize the propellers in order to avoid vibrations of the hull near the propellers.

DIESEL AND ELECTRIC DRIVE AT OVERLOAD

The geared Diesel engine is essentially a constant torque drive. As long as the fuel cut-off ratio of the engine remains unchanged, the torque developed will remain constant, regardless of speed.

The electric propeller motor is a constant power machine; i.e., the electric power supplied by the Diesel generator remains constant and the torque in the propeller shaft increases as the propeller speed decreases due to increased propeller load. Such an increase in load may result from increased wave or wind resistance or increased draft. The speed loss will be smaller in case of the constant power electric drive. On the other hand, the increase in torque is accompanied by an increase in stress in the propeller shaft and blades, requiring larger shaft diameters and heavier blades.

Summarizing, it should be kept in mind that there is not one ideal type of drive applicable to all problems of ship propulsion. The present survey points out some of the main considerations leading to adoption of one type or the other.

It is also well to note the limitations of general studies such as the one presented here. It shows trends, illustrated by specific examples. In the case of a definite design, a detailed study of all questions must be made.

TABLE II—COMPARISON OF SPECIFIC FUEL CONSUMPTIONS OF DIFFERENT PROPULSIVE SYSTEMS (AVERAGE VALUES)

Type of powerplant	*Specific fuel consumption, lbs./shp.-hr.*
Diesel, gear transmission	0.39-0.42
Diesel, electric transmission	0.44-0.46
Diesel, average, all drives	0.44
Steam turbine, average, all drives	0.66

Appendix

PROPULSIVE COEFFICIENT AND EFFICIENCY

In order to show the relation between the power developed by the engine and the speed of the ship, some definitions are presented here.

The power delivered by the working substance to the piston of the Diesel engine is the indicated power, *ihp*, as found from the indicator p-v-diagram.

At the coupling or brake the

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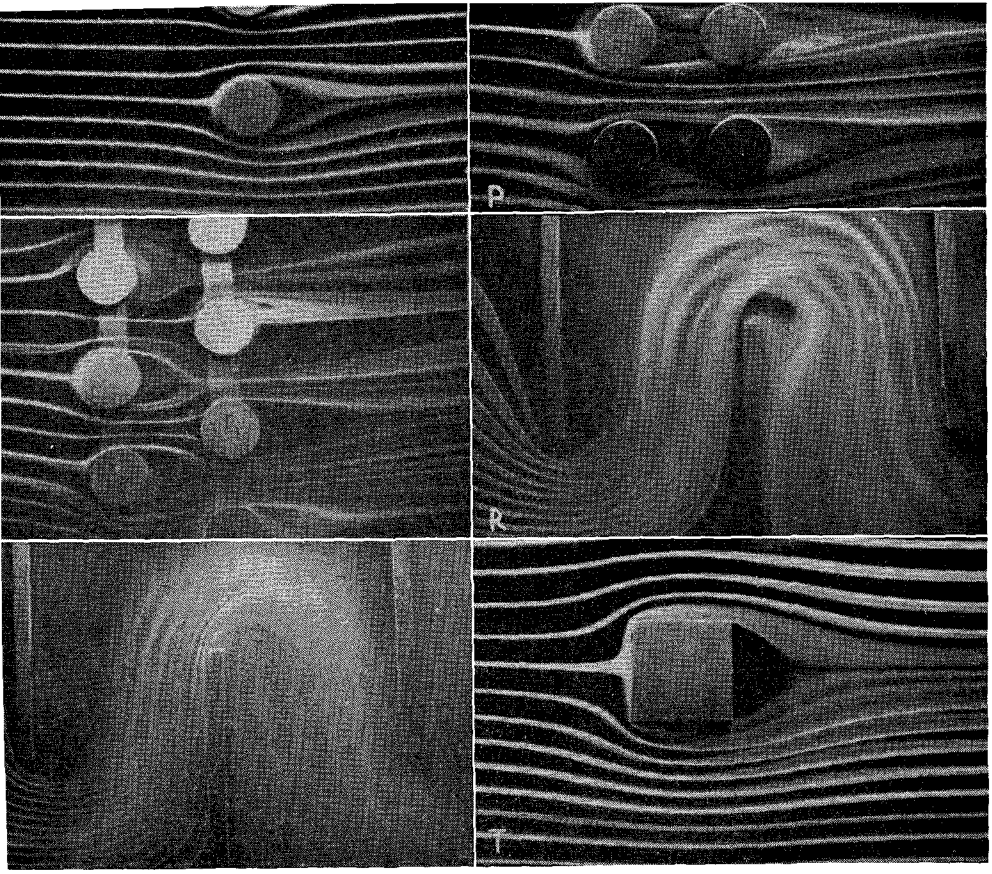

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Fig. 3. (Continued)

are important, whereas in other problems it is necessary to investigate three-dimensional flow.

The apparatus cannot be operated continuously for a long time because of the clogging of small passages and the depositing of white particles on the glass plates. Thus frequent cleaning is necessary for continued operation. It is necessary to make suitable arrangements for exhausting the mixture of air and smoke so that it cannot irritate the human body or corrode steel surfaces. Piping the exhaust outside to the open atmosphere is usually a satisfactory arrangement.

Placing an open dish of ammonium hydroxide upstream from the smoke tube makes the smoke more dense. Tin tetrachloride can be used instead of titanium tetrachloride. Dry ice might be used for generating smoke, but it offers some disadvantages as far as continuous handling and control are concerned. Kerosene vapor forms a good dense smoke, but it is difficult to control and generate without igniting.

Baffles and screens can be arranged at different places in the air stream to control the flow and make it uniform. For test purposes the glass plates can be arranged in a horizontal plane with the top plate simply resting on the model and the gaskets along the edges. Models can be changed easily with this arrangement. For instructional purposes the glass plates can be clamped together along the edges and mounted in a vertical plane. A series of lights and a reflector along the top edge of the apparatus can be provided for showing the flow patterns to large groups.

arrangement, shows a marked separation of the fluid and a considerable disturbance of the flow.

In some pieces of equipment it may be highly desirable to induce eddying flow. Figs. No. 3-P and 3-Q show two different types of cylinder arrangements; each might represent a bank of boiler tubes. The flow in Fig. No. 3-Q is probably more desirable as far as heat transfer is concerned.

USE OF APPARATUS

For low velocities the streamlines approximate the two-dimensional flow of a frictionless incompressible fluid. In some problems studies of this type of flow

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engine delivers the brake power, *bhp*, which is equal to the indicated power minus the mechanical losses in the engine. From this mechanical efficiency $= \frac{bhp}{ihp}$.

From the coupling to the stern tube bearing, power is lost in bearing friction, and, if a transmission is present, in friction in the transmission. The ratio of power actually delivered to the propeller, divided by the brake power delivered by the engine, is called transmission efficiency.

The power required to overcome the resistance of the ship at a given speed is called the effective power, *ehp*, and is equal to the product of speed and resistance. The ratio of effective power over propeller power, *ehp/php*, is called propulsive efficiency. Propulsive efficiency can be subdivided into propeller efficiency, hull efficiency and relative rotative efficiency, which represents the effect of the wake on the propeller. It is seen that all sources of loss between the combustion chamber of the engine and the power represented by the motion of the ship are accounted for. The product of the above terms is called propulsive coefficient and can be written:

$$\text{Propulsive coefficient} = \left(\frac{ehp}{php}\right)\left(\frac{php}{bhp}\right)\left(\frac{bhp}{ihp}\right) = \frac{ehp}{ihp}.$$

In connection with Diesel drives, propulsive coefficient is often used to denote the ratio $\frac{ehp}{bhp}$.

We then have the relation

$$\frac{ehp}{ihp} = \left(\frac{ehp}{bhp}\right)\left(\frac{bhp}{ihp}\right) = \left(\frac{ehp}{bhp}\right) \text{mechanical efficiency.}$$

For electric drive the above equations remain unaltered. Only the transmission efficiency is modified to account for the losses in electrical transmission.

References.

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Magg, J. *Dieselmaschinen, V.D.I.* Berlin, 1928.