

STEAM-ENGINE DESIGN.

FOR THE USE OF

MECHANICAL ENGINEERS, STUDENTS, AND
DRAUGHTSMEN.

BY

JAY M. WHITHAM, M.E., C.E.,
AUTHOR OF "CONSTRUCTIVE STEAM-ENGINEERING."

"Practice varies; but principles are eternal."

THIRD EDITION, REVISED.

SECOND THOUSAND.

210 ILLUSTRATIONS.

NEW YORK:
JOHN WILEY & SONS.
LONDON: CHAPMAN & HALL, LIMITED.
1898.

CONTENTS.

INTRODUCTION.

ART.		PAGE
1.	Types of Engines,	I
2.	Clearance,	I
3.	Piston Speed,	2
4.	Friction,	4
5.	Fuel Economy,	5
6.	Weight of Parts,	5
7.	Radiation of Heat,	5

CHAPTER I.

PISTON AREA, PISTON-HEAD, THICKNESS OF CYLINDER, BOLTS, ETC., FOR A NON-COMPOUND ENGINE.

8.	Diameter of Cylinder,	7
9.	Example on Same,	10
10.	Length of Cylinder, Cylinder Bore, Thickness of Piston, Flange and Follower,	11
11.	Design of Piston by Empirical Methods,	21
12.	Design of Piston by Analytical Methods,	22
13.	Example on Same,	24
14.	Cylinder Design,	25
15.	Example on Same,	29
17.	Design of Valve Ports,	31

CHAPTER II.

DESIGN OF SLIDE-VALVES.

18.	Kinds of Valves,	32
19.	Square Slide-valves,	32
20.	Expansion Slide-valves,	33
21.	Zeuner's Diagram for a Square Valve,	35
22.	Zeuner's Diagram Considering Lap and Lead, and Problems,	37
23.	The Allen Slide-valve,	46
24.	Gozenbach or Gridiron-valve,	49
25.	Problems on Same,	54

CONTENTS.

CHAPTER X.

DESIGN OF THE CONNECTING-ROD.

ART.	PAGE
82. Diameter of the Connecting-rod,	217
83. Design of the Connecting-rod Ends,	219

CHAPTER XI.

DESIGN OF THE CRANK-PIN.

84. Friction of the Crank-pin,	228
85. Length of the Crank-pin to Avoid Heating,	231
86. Diameter of an Overhung Crank-pin,	233
87. Design of the After Crank-pin Diameter for a Two-cylinder Engine,	234
88. Design of the After Crank-pin Diameter for a Three-cylinder Engine,	237

CHAPTER XII.

DESIGN OF THE CRANK-ARMS, CRANK, LINE AND PROPELLER SHAFTS,
BEARINGS AND COUPLINGS.

89. Design of the Crank-arm Eyes,	239
90. Design of the Crank-arm,	241
91. Design of the Crank-shaft for a Single Engine,	244
92. Design of the Crank-shaft for a Two-cylinder Engine,	248
93. Design of the Crank-shaft for a Three-cylinder Engine, Cranks 120°,	252
94. Design of the Crank-shaft for a Three-cylinder Engine with L. P. Crank Opposite and H. P. Crank Midway,	253
95. Design of the Line-shaft,	254
96. Design of the Thrust or Propeller Shaft for a Marine Engine,	254
97. Design of Crank- and Line-shaft Bearings,	259
98. Design of a Thrust Bearing for a Propeller Engine,	263
99. Shaft-couplings,	266
100. Board of Trade's Rules for Shafting,	272
101. Practical Rules for Shafting,	273

CHAPTER XIII.

CONDENSERS AND PUMPS.

102. Surface Condensers,	276
103. Thermal Experiments and Deduction of a Formula for the Condensing Surface,	278
104. Quantity of Condensing Water,	285
105. Design of Parts of a Surface Condenser,	285
106. Design of a Jet Condenser,	294
107. Design of the Injection Orifice,	298
108. Design of the Air-pump,	301
109. Design of the Circulating Pump,	308
110. Design of the Feed-pump,	314

CONTENTS.

ix

ART.	PAGE
111. Flow of Water Through Pipes,	317
112. Design of a Pump to Deliver Against a Head of Water,	321

CHAPTER XIV.

ENGINE FRAME, PILLOW-BLOCKS, REVERSING ENGINE, PIPES, STOP-VALVES,
COCKS, EXPANSION JOINTS, SCREW-THREADS, AND WALKING-BEAMS.

113. Foundations,	324
114. Engine Frames,	327
115. Pillow-blocks,	329
116. Distance between Shaft-bearings,	331
117. Power Required for Reversing and Pumping Engines,	333
118. Size and Strength of Pipes,	335
119. Distance Between Hangers for a Pipe,	337
120. Design of Stop-valves,	338
121. Design of Cocks,	340
122. Design of Expansion joints,	343
123. Standard Screw-threads,	344
124. Walking-beams,	349

CHAPTER XV.

PROPELLING INSTRUMENTS AND THE POWERING OF VESSELS.

125. Theory of the Propeller,	353
126. The Indicated Horse-power for Vessels,	355
127. Radial Paddle-wheel,	358
128. Design of a Feathering Paddle-wheel,	360
129. Design of Parts of a Paddle-wheel,	365
130. The Screw-propeller,	368
131. The Diameter and Pitch of the Screw,	371
132. Area of Screw-blades and their Dimensions,	372
133. Kinds of Screw-propellers,	375

APPENDIX.

134. Strength of Materials,	381
135. Saturated-steam Table,	385
136. Supplement to § 65,	387

STEAM-ENGINE DESIGN.

INTRODUCTION.

1. Types.—The efficiency of a steam-engine for any particular duty depends largely upon the type selected. In choosing any particular type, we must endeavor to secure one which has the greatest number of advantages and the least number of disadvantages. Since the designer is familiar with the various types of engines in use, only the conditions governing him in making his selection will be enumerated.

These conditions are, briefly :

1. Clearance.
2. Piston speed.
3. Friction.
4. Economy of fuel.
5. Weight and complexity of moving parts.
6. Accessibility for repairs.
7. Radiating surface.

2. Clearance is the volume included between the piston, when at the end of its stroke, and the valve-seat. The distance between the piston, when at the end of its stroke, and the cylinder-head is sometimes (inaccurately) called clearance. This latter is *piston* and not *engine* clearance.

Clearance is measured as a certain percentage of the stroke displacement of the piston. As the clearance volume is nearly constant for any fixed diameter, the percentage is greater for short- than for long-stroke engines. Hence it is well to have the stroke as long as possible, in order to eliminate the prejudicial effect of clearance. If the stroke is fixed, the clearance volume will be nearly directly proportional to the square of the diameter of the cylinder.

CHAPTER I.

DESIGN OF PISTON AREA, PISTON, THICKNESS OF CYLINDER, BOLTS, ETC., FOR A NON-COMPOUND ENGINE.

8. Diameter of Cylinder.—Having determined upon the power of the engine, its type, speed of piston, initial and terminal pressures of steam in the cylinder, we are prepared to begin the design of the parts for the duty required of them.

From § 3 we have

$$a = \frac{33000 \times \text{I. H. P.}}{p_e l n},$$

in which a = area of the piston in square inches ;

I. H. P. = indicated horse-power of the engine ;

p_e = mean effective or unbalanced pressure on each square inch of the piston in pounds ;

l = length of stroke in feet ;

n = number of strokes per minute ;

Let p_1 = initial absolute pressure of steam in pounds per square inch at the cylinder ;

p_B = initial absolute pressure of steam at the boiler ;

p_2 = terminal absolute pressure of steam, or driving pressure at the end of the stroke ;

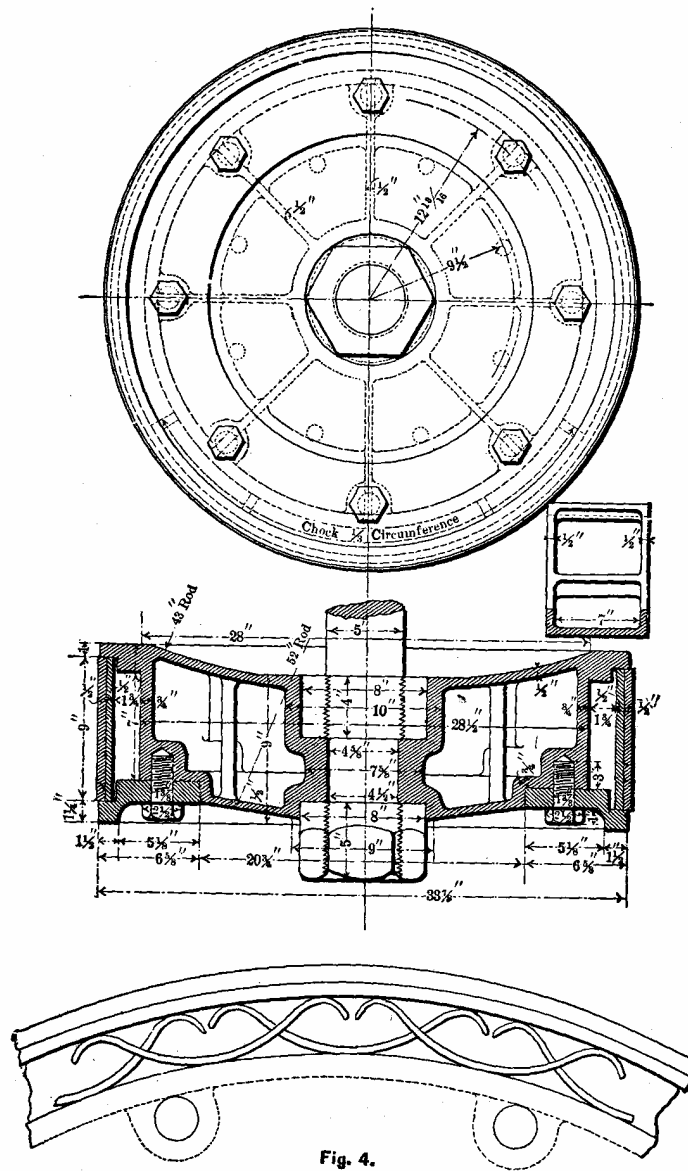
p_3 = mean absolute back pressure against the piston per square inch ;

p'_m = mean absolute driving pressure throughout the stroke in pounds per square inch.

If the pipe conveying the steam from the boiler to the steam-chest is short, direct, and lagged, the fall will not exceed $\frac{1}{13}$ of p_B , or

$$p_1 = \frac{12}{13} p_B.$$

Since the steam filling the clearance volume expands with that in the cylinder proper, we will divide the volume of clearance by the area of the piston, and find the length of cylinder



the late Mr. George H. Corliss by swelling the outer thickness about the middle of the cylinder's length.

Whenever the two cylinders are made in two parts, it is necessary to make a steam-tight joint at the free end of the bushing. This is done in various ways, but frequently the joint is made so tight that there is left no space for free expansion of the bush over the casing. In such a case the bushing has no special advantages. This is likely to occur only with long-stroke engines. To overcome this objection, Mr. E. D. Leavitt, Jr., casts the outer cylinder in two parts, and connects them by a swelled copper joint, extending circumferentially around them.

Fig. 18 is a drawing (from *Engineering*, xxii.) of the high-pressure jacketed cylinder of the U. S. S. *Nipsic*. The flat surfaces are to be proportioned by formulæ given in Chapter IV. The jacket-joint is made by brass or Babbitt metal rings which are forced into place by the screws, the screws abutting against the inside of the cylinder-head. The head has a man-hole. In Fig. 60 is illustrated a form of plain cylinder.

15. EXAMPLE.—Design the cylinder and cylinder-head for $D = 37.25$, $P = 69$ lbs.

$$\begin{aligned} \text{Thickness of cylinder-head} &= \frac{37.25 \times 69 + 500}{2000} \\ &= 1.54 \text{ inches (Seaton, § 11).} \end{aligned}$$

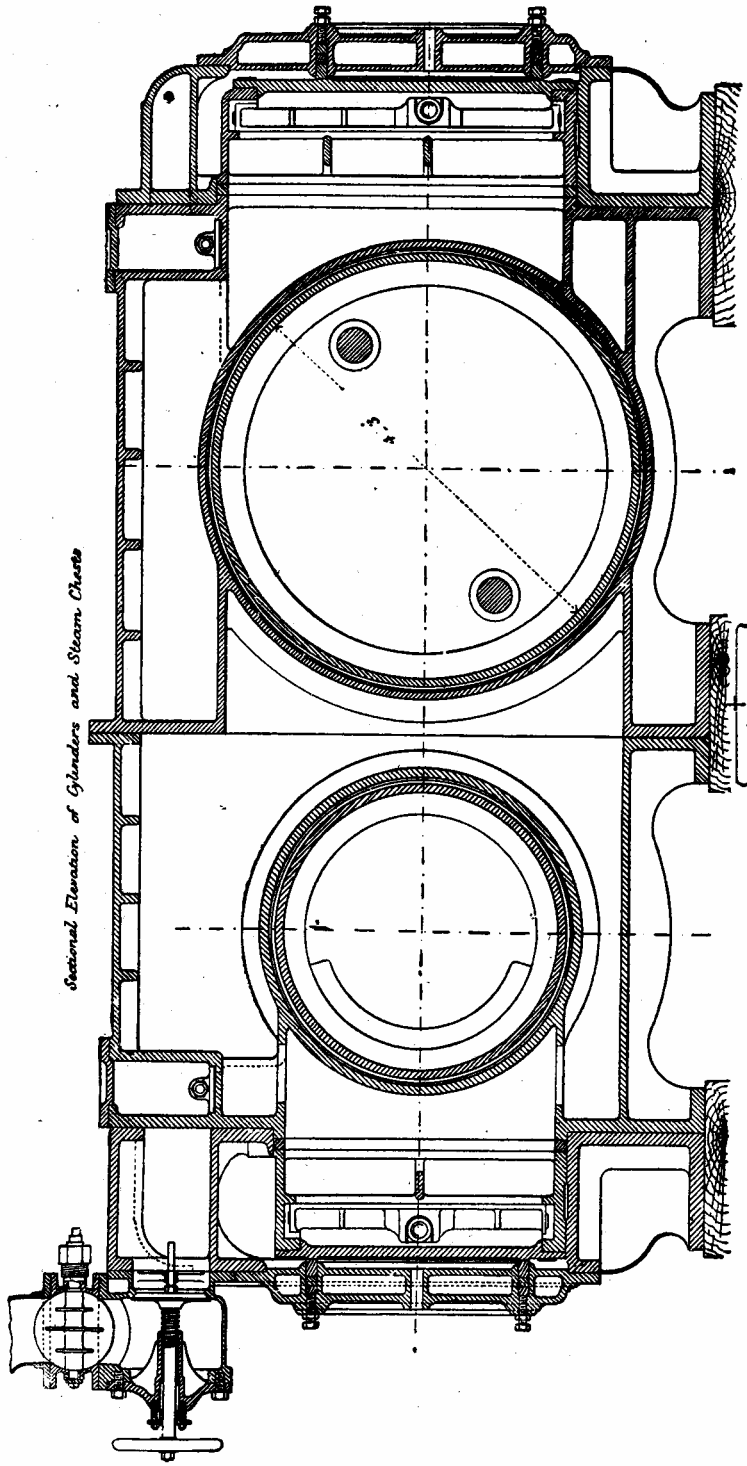
$$\begin{aligned} \text{Thickness of cylinder-head at flange} &= \frac{37.25 \times 69 + 500}{1500} \\ &= 2.05 \text{ inches.} \end{aligned}$$

$$\begin{aligned} \text{Thickness of cylinder} &= 0.03 \sqrt{37.25 \times 69} \\ &= 1.52 \text{ (Van Buren).} \end{aligned}$$

Diameter of bolt-circle for the cylinder-head = $37.25 + 2 \times 1.52 + 2 \times \text{diameter of the bolt} = 42$ inches, on the assumption that the bolts are about $\frac{7}{8}$ inch in diameter.

The bolts should not be more than 6 inches apart. If they are 5.5 inches pitch there will be 24 bolts required.

The safe tensile strength of the 24 bolts must be equal to the maximum load on the cylinder-head, or



Sectional Elevation of Glinders and Steam Chests

30

Fig. 18

$$24 \times \frac{\pi d^2}{4} \times 5000 = 69 \times 0.7854 \times (37.25)^2;$$

$$d = 0.89 \text{ inch} = \text{effective diameter of bolt.}$$

In this, 5000 is taken as the safe tensile strength of wrought-iron, and no allowance is made for the counter-bore of the cylinder.

17. Design of Valve-ports.—The ports or passages through which the steam passes in going from the valve-chest to the cylinder must be short, direct, of easy curvature, and large enough to prevent “wire-drawing” of the steam.

Length of port = 0.8 diameter of cylinder;

Area of exhaust port = $\frac{2}{3}$ area of steam-port.

Steam flowing at the velocity of 6000 ft. per min. (see § 3, and Rankine's *Steam Engine*) passes through the steam-port into the cylinder, where the piston is moving at from 100 to 1000 ft. per min. Hence, applying the “law of continuity” of fluids to a current of steam,

$$a = \frac{AV}{v} = \frac{\text{area piston} \times \text{piston's speed}}{6000};$$

where a = area of valve-port in sq. inches;

A = “ “ piston in square inches;

v = velocity of steam flowing through the port = 6000 ft. per min.;

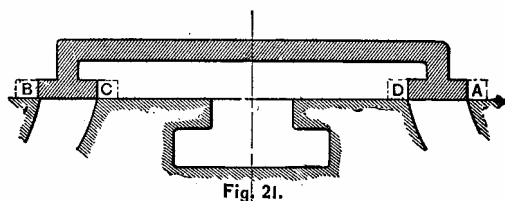
V = velocity of piston in ft. per min.

The length of the port is long in comparison with its width, and the steam passages short and direct, in order that the clearance volume may be small.

CHAPTER II.

DESIGN OF SLIDE-VALVES.

18. Kinds of Valves.—A slide-valve regulates the admission and emission of steam to and from the cylinder. In order that it may be operated so as to produce the best effect, the steam space in the boiler must be large enough to give a uniform flow, and the communicating steam-pipe must not be too small or long, or have sharp bends. Valves are called oscillating, rotating, poppet, reciprocating, etc., according to their movement and form. The plane, reciprocating valve is called the slide-valve, and is in general use.



19. Square Slide-valves.—The slide-valve moves over a plane surface called the *valve-seat*. The under side of the valve is called its *face*. The square slide-valve has three ports in its seat, one at each end for the live steam to enter, and through which the steam is finally emitted as exhaust, and discharged into the central passage called the exhaust-port. The movement of the valve is controlled by an *eccentric*. This is a disk set eccentric to the shaft on which it is secured. The *throw of the eccentric* is the distance between the centre of the shaft and centre of the eccentric. The throw is usually equal to one

$AD = 4$ ft.; the scale for the eccentric orbit is $HB = 3$ in.; and the scale for pressures, 45 lbs. = 1 inch.

The steam enters at crank position OA , and closes at $\frac{5}{8}$ stroke, or OC ; therefore the steam-port is wide open when the crank

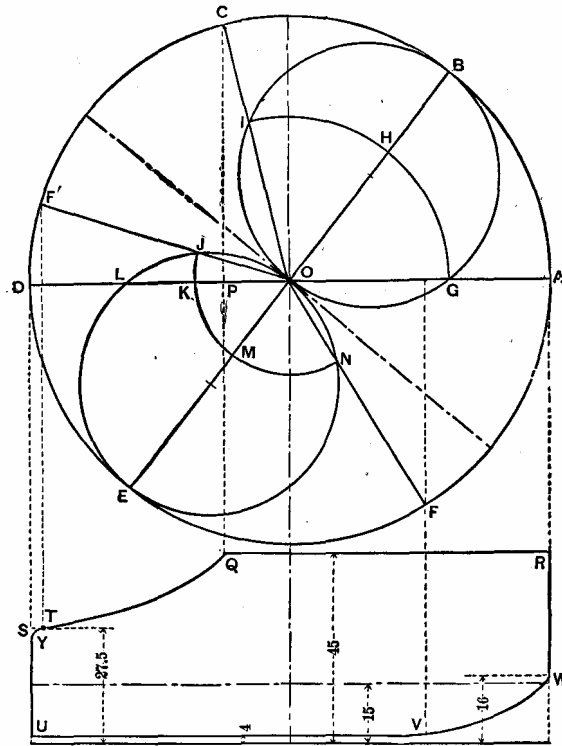


Fig. 27.

is midway between A and C , or at OB . OB is the valve-circle, OG is the steam-lap = OH , and HB is the 3-in. steam-port width given. On the scale that $BH = 3$ in., the lap $OH = 5$ in. The throw of the eccentric is ($OH + HB =$) 8 in. The exhaust-valve closes when the crank is at OF , or 12 in. from the end of the stroke, compressing steam of $\left(\frac{30 - 22}{2} =\right)$ 4 lbs. pressure to $\left(4 \times \frac{12 + 4}{4} =\right)$ 16 pounds.

Steam-lap at the inner end of the valve = 1.11 in. = KO ;
 Exhaust-lap at the inner end of the valve = 1.22 in. = HO ;
 Point of cut-off for stroke from inner end = 20 in.

Fig. 30 is a sketch, from Seaton's *Manual of Marine Engineering*, of this valve.

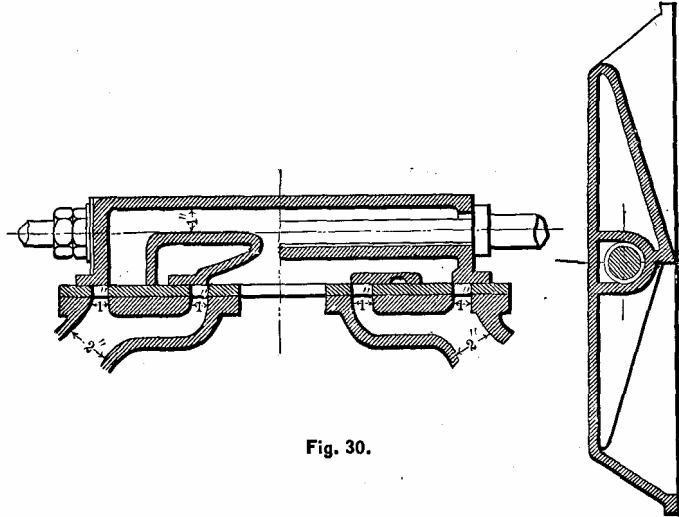


Fig. 30.

EXAMPLE 4. Fig. 31 is a sketch of a valve in use. The stroke of the piston is 36 in.; throw of the eccentric, 3 in.; length of the connecting-rod, 72 in.; clearance, $\frac{1}{2}$ of the stroke-displace-

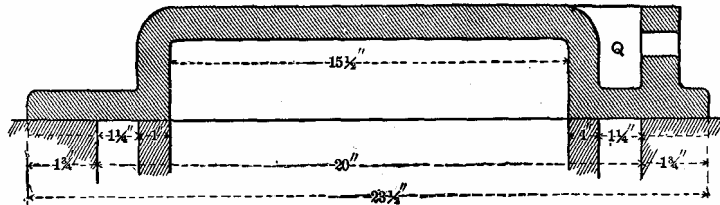


Fig. 31.

ment; the steam-port is open $\frac{1}{4}$ in. when the engine is on either centre; initial absolute pressure of steam, 45 lbs. per square inch; and the back pressure, 4 lbs. Required the point of cut-off for each stroke, position of the piston when the steam-port

APPENDIX.

134. Strength of Materials.—The following table is given on the authority of Rankine, Kirkaldy, Fairbairn, Wade, Barlow, Telford, Anderson (Com. B. A.), Shock, Lloyd, Hodgkinson, Trautwine, and others. The values refer to the ultimate resistance of the material in pounds per square inch of cross-section.

METAL.	Tension.	Compression.	Shearing.	Transverse or breaking-across.	Modulus of elasticity.
Iron, cast, average.....	16,500	86,000	19,000 to 28,000	17,000	18,270,000
“ “ with scrap.....	28,000				
“ “ pig.....	13,000				
“ “ first melting.....	20,800				
“ “ 2d “.....	24,700	99,680			
“ “ 3d “.....	26,800	140,000			
“ “ hot blast.....		111,300			
“ “ cold “.....		99,200			
Iron, wrought, bars, English.....	50,000 to 66,000	33,000 to 36,000	40,000 to 46,000	40,000	28,000,000
“ “ “ American.....	45,000 to 70,000	“	“	“	“
“ “ large forgings.....	35,000	33,000			
“ “ hammered bars.....		to 36,000			
“ “ plates.....	45,000 to 65,000				
“ “ “ beams.....				40,000 to 42,000	
Steel, plate, American.....	50,000 to 95,000				
“ “ Bessemer.....	95,000 to 112,000				
“ rolled and hammered ingots.....	125,000				
“ bar.....	95,000 to 120,000		82,800		36,000,000 to 42,000,000
“ “ tempered.....	214,400	50,000 to 60,000			
“ chrome.....	180,000				
“ cast.....		225,000			
Steel, hematite bar.....		159,578			
“ American black diamond.....		102,500			
Copper, wrought.....	33,600	103,000			
“ sheet.....	30,000				
“ cast.....	20,000	117,000			
Gun metal, bronze.....	33,000 to 36,000				10,000,000
Bronze, 8 Cu, 1 Sn.....					9,900,000
Brass, cast.....	18,000	16,480			9,170,000
Aluminum bronze, 90 Cu, 1 Al.....	73,181				
Phosphor “.....	34,465				

135. Saturated Steam Table.—The following table is taken from Northcott's treatise on *The Steam-Engine*:

Absolute pressure in pounds per square inch.	Temperature of boiling-point in degrees Fahr.	Cubic feet of steam weighing one pound.	Latent heat of vaporization per pound of steam generated under a constant pressure.	Total heat units required to generate one pound of steam from water at 32° F. under a constant pressure.
0.0	-461.2
0.085	32	3390.0	1091.70	1091.70
1.00	102	332.6	1043.02	1113.05
1.25	109.6	269.3	1037.98	1115.62
1.50	115.8	226.8	1033.41	1117.26
1.75	121.3	196.1	1029.58	1118.94
2.00	126.4	173.0	1026.02	1120.49
2.50	134.8	140.1	1020.17	1123.06
3	141.6	118.0	1015.43	1125.14
3.5	147.8	102.16	1011.09	1127.02
4	151.1	90.12	1007.38	1128.63
4.5	157.8	80.67	1004.10	1130.07
5	162.3	73.50	1000.95	1131.44
5.5	166.4	66.77	998.08	1132.69
6	170.1	61.50	995.49	1133.82
6.5	173.5	57.03	993.11	1134.86
7	176.9	53.16	990.73	1135.90
7.5	180.0	49.79	988.55	1136.84
8	183.0	46.83	986.44	1137.75
9	188.4	41.87	982.66	1139.40
10	193.3	37.87	979.22	1140.89
11	197.8	34.60	976.06	1142.26
12	202.0	31.85	973.12	1143.55
13	205.9	29.51	970.36	1144.72
14	209.6	27.50	967.78	1145.87
14.7	212.0	26.36	966.08	1146.60
15	213.1	25.86	965.31	1146.93
16	216.3	24.32	963.06	1147.91
17	219.5	22.97	960.81	1148.89
18	222.5	21.76	958.68	1149.80
19	225.3	20.68	956.76	1150.62
20	228.0	19.70	954.79	1151.47
21	230.7	18.82	952.89	1152.30
22	233.3	18.01	951.05	1153.09
23	235.8	17.27	949.28	1153.85
24	238.2	16.60	947.58	1154.58
25	240.5	15.97	945.96	1155.29
26	242.7	15.39	944.40	1155.96
27	244.8	14.86	942.91	1156.60
28	246.8	14.36	941.50	1157.21
29	248.7	13.89	940.15	1157.79
30	250.5	13.46	938.87	1158.34
32	254.0	12.67	936.39	1159.41
34	257.4	11.97	933.98	1160.45
36	260.7	11.35	931.61	1161.46
38	263.9	10.79	929.36	1162.43
40	267.0	10.28	927.16	1163.38

INDEX

(The numbers refer to pages.)

- AIR-PUMP, design of, 305:
parts of, 302.
various kinds of, 295, 301.
- Alloys for bearings, 23, 229.
for engines, table, 229.
for pistons, 23.
for screw propellers, 374.
strength of, 374, 381.
- Area of valve-ports, 31, 98.
- BARS, eye, proportions of, 118 *et seq.*
- Beams, formula for, 383.
- Beam, walking, 350.
- Bearing, brasses for, 224, 329.
crank-shaft, 241, 259.
design of, 329.
distance between, 331.
friction of, 4, 189.
line-shaft, 259.
length of, 262.
materials for, 23, 229.
(*see* Pillow-blocks).
stern, 255.
thrust, 263.
various forms of, 261.
- Bolts, 346.
for connecting-rods, 221.
for couplings, 266.
for foundations, 326.
for valve-chests, 97.
for valve-gears, 114.
- Brake, block, 272.
friction, 268, 271.
- CLEARANCE, definition, 2.
how measured, 2, 8, 67.
of valve-ports, 31.
piston, 1, 2.
- Circulating pump (*see* Pump).
- Centrifugal pumps (*see* Pump).
- Cocks, plug, 340.
- Compound engine, cylinder ratio, 151, 155, 157, 160.
cylinder diameters by graphics, 152, 153.
cylinder diameters by methods compared, 155.
cylinder diameters by no "drop" method, 143.
cylinder diameters by Rae's method, 140.
cylinder diameters by Rankine's method, 145.
cylinder diameters by Seaton's method, 146.
indicator cards of, 161 *et seq.*
kinds of, 128, 160.
theory of, 131 *et seq.*
triple-expansion, 155, 157, 160.
triple-expansion, kinds of, 160.
- Condensers, jet, Davidson's, 302.
jet, steam inlet, 294.
jet, water outlet, 294.
jet, water used, 285, 294.
jet, Worthington's, 295, 298.
jet, thickness of shell, 294.
jet, various forms of, 294, 295, 298, 302.
jet, volume of, 294.
jet, volume of steam, 284.
surface, advantages, 277.
surface, deduction of formula, 280, 283.
surface, experiments on, 278, 279, 283.
surface, rules for surface, 276, 277, 283.
surface, steam used, 284.
surface, theory of a, 276, 280.
surface, thickness of shell, 288.
surface, tube area, 291.

- Condensers, surface, tube length and thickness, 294.
 surface, tube materials used, 294.
 surface, tube packings, 290.
 surface, various kinds, 285, 288, 291, 298.
 surface, water for condensing, 285.
- Connecting-rod diameter, 217, 219.
 ends, 219, 224.
 forms of, 225.
- Couplings for pipes, 348.
 for shafts, 266, 270.
 for shafts, bolts used, 270.
- Crank-arm, design, 239.
 eyes, 239.
 keys, 125, 244.
 shapes, 241.
- Crank-effort, affected by friction, 191, 194.
 affected by weight of parts, 173 *et seq.*
 diagrams, 169 *et seq.*
 meaning of, 168.
 relation to fly-wheel, 199.
- Crank-pin, 228.
 boxes, 228.
 diameter, 233, 234, 237.
 dead-point, 33.
 friction, 228.
 length, 231.
 locomotive, 232.
 pressures, 232.
 proportions, 232.
- Crank-shaft design, 244, 248, 252, 253.
 forms of, 241.
 loads on, table, 246.
- Cross-head, design, 213.
 friction of, 4, 187.
 forms of, 213 *et seq.*
- Cylinder bore, 11.
 clearance, 1, 2, 8, 11, 31, 67.
 (*see Compound engines*).
 design, 25.
 diameter, 6, 7, 10.
 head, 25, 29.
 jacket and joints, 28.
 length, 6, 11.
 materials for, 25.
 of pumps (*see Pumps*).
 radiating surface, 6.
 relief valve, 317.
 reversing, 333.
 thickness of, 26.
 triple-expansion engine (*see Compound engine*).
- ECCENTRIC, angular advance of, 33.
 (*see Valve-gears*).
- Eccentric rods (*see Valve-gears*).
 strap (*see Valve-gears*).
 throw, 32, 35.
- Economy of fuel, 5.
- Engine, centres, 33.
 compound (*see Compound Engine*)
 dead points, 33.
 for reversing valves, 333.
 foundations, 324.
 frames, 327.
 friction (*see Friction*).
 holding-down bolts, 326.
 horse-power of (*see Horse-power*).
 moving parts of, 5, 169, 199.
 triple-expansion (*see Compound Engine*).
 types of, 1, 128, 160.
 work done by, 4, 191, 353, 357, 370.
- Expansion joints, 28, 343.
 of metals, 343.
- Eye-bars, proportions of, 118 *et seq.*
- FLAT PLATES, thickness of, 95.
- Flow of water through pipes, 317.
- Fly-wheel, design of, 199.
 kinds of, 203.
- Foundations of engines, 324.
- Frames of engines, 327.
- Friction of bearings, 4, 189, 229.
 of brakes, 268, 271, 272.
 of cross-head, 187.
 of crank-pin, 189, 228.
 of effects on turning power, 191, 194.
 of engine, 4, 191.
 of guide, 4, 5, 187.
 of journals, 4, 189, 229.
 of piston, 186.
 of pipes, 319.
 of pumps, 321.
 of propellers, 371.
 of ship's wetted surface, 355, 357.
 of stuffing-box, 186.
 of valve, 111.
 of wrist-pin, 188.
- Fuel, economy of, 5.
- GUIDE, design of, 209.
 distance between two, 211.
 friction of, 4, 5, 187.
 materials used for, 213.
 various forms of, 213.
- HEAT, experiments on conductivity, 6, 278, 279.
 in saturated steam, 384.
 non-conductors of, 6.
 radiation from cylinders, 6.

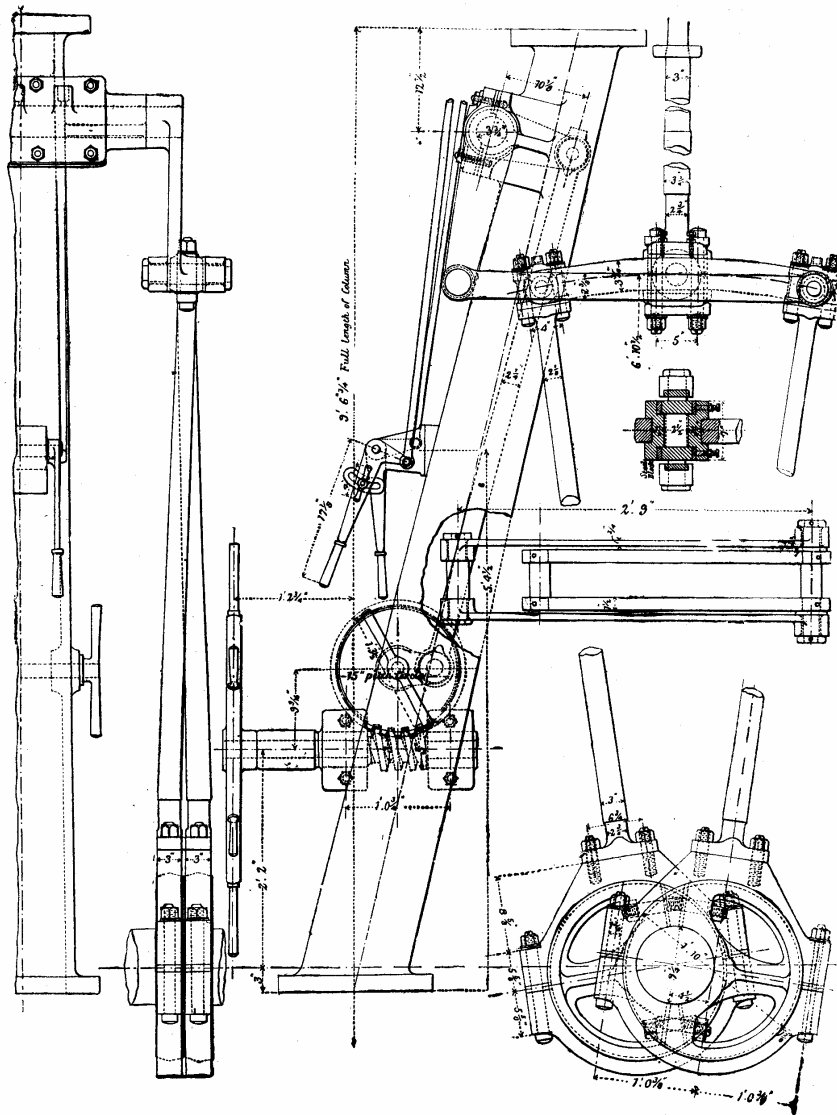


Fig. 78.

To face page 115.

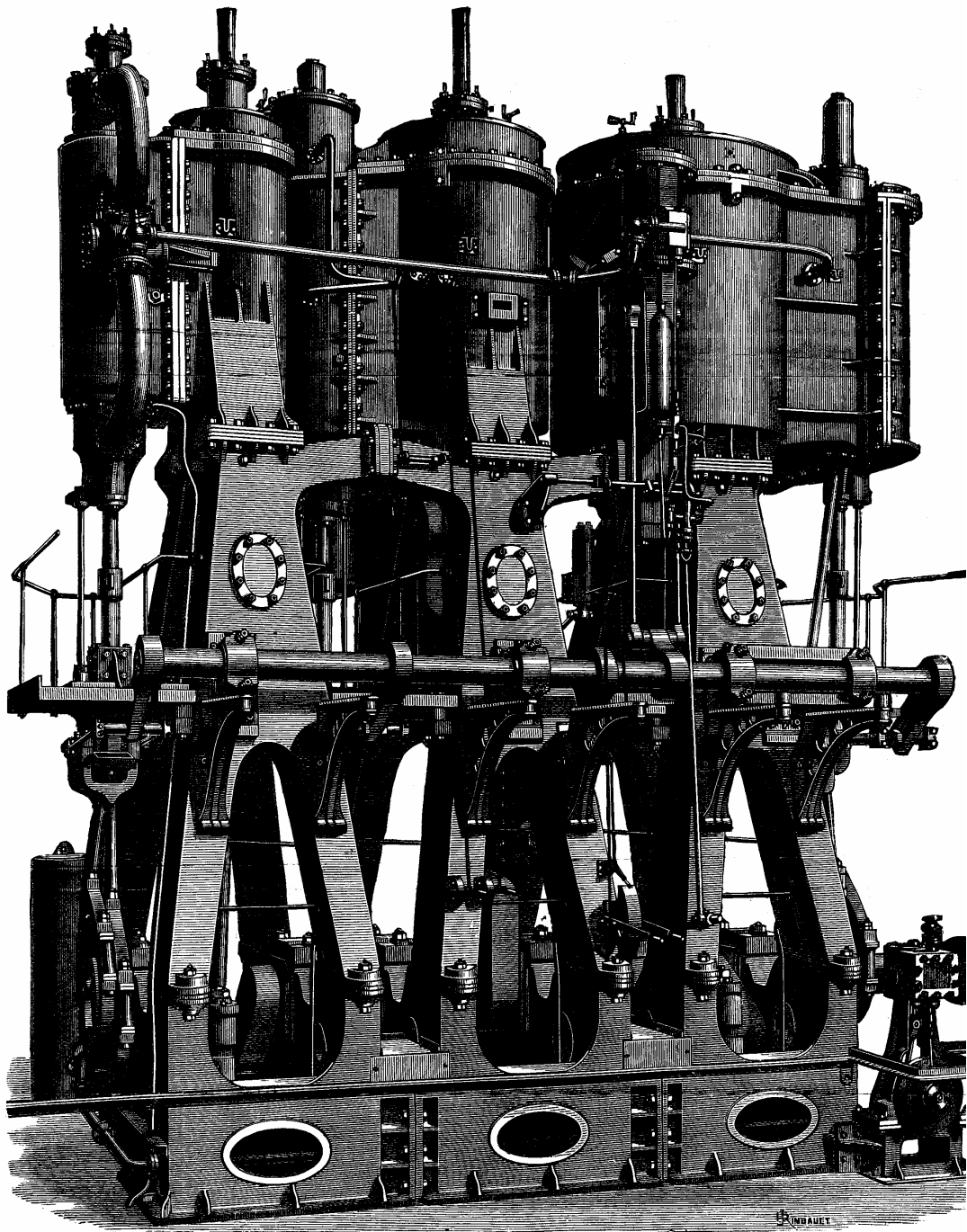


Fig. 91.

To face page 156

TRIPLE-EXPANSION ENGINE OF SS. *Aberdeen*.