Steam. Steam is water in a gaseous state. It liquefies at a temperature of 100° C., or 213° F., under a pressure of one atmosphere at sea-level, namely, 14.7 pounds per square inch. High pressure and low pressure steam once meant steam used at pressures above or below this point, but the terms have lost their significance. The standard of steam pressure in engines is constantly rising, and high or low pressure are terms understood today as of no permanent value. "Absolute steam pressure is the total pressure computed from the zero of an absolute vacuum, as distinguished from relative pressure at sea-level. Ordinary steam gauges indicate pressure above that of the atmosphere. To this must be added the pressure of the atmosphere in order to obtain the absolute steam pressure."

Saturated steam or wet steam is steam holding water in suspension mechanically, or steam in contact with water at the same temperature which is the case at its condensing or boiling point.

"When the pressure exerted by the vapor which a space contains at a given temperature has reached the limiting value for that temperature, the space is said to be saturated with the vapor. When a space is saturated with vapor the pressure exerted by the vapor is also known as saturation pressure. If the volume of a space which is saturated with vapor be reduced, some of the vapor is condensed to a liquid state, but the pressure remains the same."

"If the volume of the space be increased, provided that it contains sufficient liquid, more water evaporates and the pressure exerted by the water vapor soon attains the same value as before the change of volume."

"If the temperature of a space containing water, and its saturated vapor be raised, the saturation pressure of the vapor is increased; if on the other hand the temperature falls, some of the vapor is condensed, and the saturation pressure is less."

Superheated steam or steam-gas is steam not in contact with water, heated until it resembles a perfect gas. Dry steam is steam without any admixture of water vapor held mechanically in suspension. "Live steam" is steam which has performed no work, or rather which is available for the performance of work. Dead steam is steam which has performed work; more frequently it is called exhaust steam.

Vaporization. – When heat is applied to water, a point is reached at which the heat overcomes the cohesion and the pressure of the atmosphere, then the water passes into vapor. Evaporation takes place at the surface of the water. Its rapidity varies with the temperature and the pressure upon that surface. When a flask containing water (see Fig. 1) is placed over the flame of a lamp, the absorbed air is first driven off, then as the temperature of the water rises, the liquid molecules in contact with the bottom of the flask become so hot that the heat is able to overcome their cohesion, the pressure of the overlying water, and the pressure of the atmosphere above the water. At this temperature the change from a liquid to a gaseous state takes place beneath the surface, the gas escaping with ebullition.

FIG. 1

The temperature at which steam is formed depends on the pressure under which it is generated. This relation has been determined with great care by Regnault. Upon these determinations the practical application of steam depends in large measure. The following table compiled from Rankine's reduction of Regnault's results gives the relations between pressure, volume, and total heat of steam for temperatures between 32° F. and 428° F.

"During the first stage of heating, all the heat sensibly goes into increasing the internal energy of the fluid. This is represented in the last column of the table under the heading (h.) During the second stage the heat taken in is known as latent heat of steam. The total heat of both stages is represented by the numbers in the fourth column of the table under the heading (H.)"

TABLE I.

Tempera-ture	Pressure	Volume of one pound	Heat of formation H.	Heat of formation h.
Degrees F.	Lbs. per sq. inch	Cub. Ft.	Thermal units	Thermal units
32	0.085	3390	1091.8	0
41	0.122	2406	1094.5	9
50	0.173	1732	1097.3	18
59	0.241	1264	1100.0	27
68	0.333	935	1102.8	36
77	0.452	699	1105.5	45
86	0.607	529	1108.2	54
95	0.806	405	1111.0	63
104	1.06	313	1113.7	72
113	1.38	244	1116.5	81
122	1.78	192	1119.2	90.1
131	2.27	152.4	1121.0	99.1
140	2.88	122.0	1124.7	108.1
149	3.62	98.45	1127.4	117.1
158	4.51	80.02	1130.2	126.2
167	5.58	65.47	1132.9	135.2
176	6.87	53.92	1135.6	144.3
185	8.38	44.70	1138.4	153.3
194	10.16	37.26	1141.1	162.4
203	12.26	31.26	1143.9	171.4
212	14.70	26.36	1146.6	180.5
221	17.53	22.34	1149.3	189.6
230	20.80	19.03	1152.1	198.7
239	24.54	16.28	1154.8	207.8
248	28.83	14.00	1157.6	216.9
257	33.71	12.09	1160.3	226.
266	39.25	10.48	1163.1	235.2
275	45.49	9.124	1165.8	244.3
284	52.52	7.937	1168.6	253.5
293	64.40	6.992	1171.3	262.7
302	69.21	6.153	1174.1	271.9
311	79.03	5.433	1176.8	281.1
320	89.86	4.816	1179.5	290.3
329	101.9	4.280	1182.2	299.5
338	115.1	3.814	1185.0	308.7
347	129.8	3.410	1187.7	318.
356	145.8	3.057	1190.4	327.3
365	163.3	2.748	1193.2	336.6
374	182.4	2.476	1195.9	345.9
383	203.3	2.236	1198.6	352.2
392	225.9	2.025	1201.4	364.5
401	250.3	1.838	1204.1	373.9
410	276.9	1.672	1206.9	383.2
419	305.5	1.525	1209.6	392.6
428	336.3	1.393	1212.4	402.0

Dulong and Arago determined the tension of steam many years ago by means of the apparatus shown in Fig. 2.

In the figure (k) is a copper boiler, with a tube (a) containing a thermometer (t), which measures the temperature of the water, and its vapor. The tension of the steam is measured by a manometer (m). The steam passing through the tube (c), exerts a pressure on a column of water in the tube (i). This pressure is further transmitted to the mercury in the vessel (d), and thence to the manometer. By taking the manometer readings corresponding to each degree of the thermometer, a direct measurement of tension was obtained up to a pressure of 24 atmospheres, and from this on by calculation. The following is a table of results:

TABLE II.

Temperature	Number of atmospheres	Temperature	Number of atmospheres	Temperature	Number of atmospheres	Temperature	Number of atmospheres
100.0°	1	170.8°	8	198.8°	15	217.9°	22
112.2	1½	175.8	9	201.9	16	220.3	23
120.6	2	180.3	10	204.9	17	222.5	24
133.9	3	184.5	11	207.7	18	224.7	25
144.0	4	188.4	12	210.4	19	226.8	26
152.2	5	192.1	13	213.0	20	228.9	27
159.2	6	195.5	14	215.5	21	230.9	28
165.3	7						

Regnault, 14 years later, devised a method by which the vapor of water could be measured at temperatures above or below boiling point. By this method the following tensions were obtained for temperatures ranging from 10° below to 101° above zero, of the Centigrade scale.

TABLE III.

Temperature degrees	Tensions in millimeters	Temperature degrees	Tensions in millimeters	Temperature degrees	Tensions in millimeters	Temperature degrees	Tensions in millimeters
−10	2.078	12	10.457	29	29.782	85	433.41
8	2.456	13	11.602	30	31.548	90	525.45
6	2.890	14	11.906	31	33.405	91	545.78
4	3.387	15	12.699	32	35.359	92	566.76
2	3.955	16	13.635	33	37.410	93	588.41
1	4.600	17	14.421	34	39.565	94	610.74
+1	4.940	18	15.357	35	41.827	95	633.78
2	5.302	19	16.346	40	54.906	96	657.54
3	5.687	20	17.391	45	71.391	97	682.03
4	6.097	21	18.495	50	91.982	98	707.26
5	6.534	22	19.659	55	117.478	98.5	720.15
6	6.998	23	20.888	60	148.791	99.0	733.21
7	7.492	24	22.184	65	186.945	99.5	746.50
8	8.017	25	23.550	70	233.093	100.0	760.00
9	8.574	26	24.998	75	288.517	100.5	773.71
10	9.165	27	26.505	80	354.643	101.0	787.63
11	9.792	28	28.101				

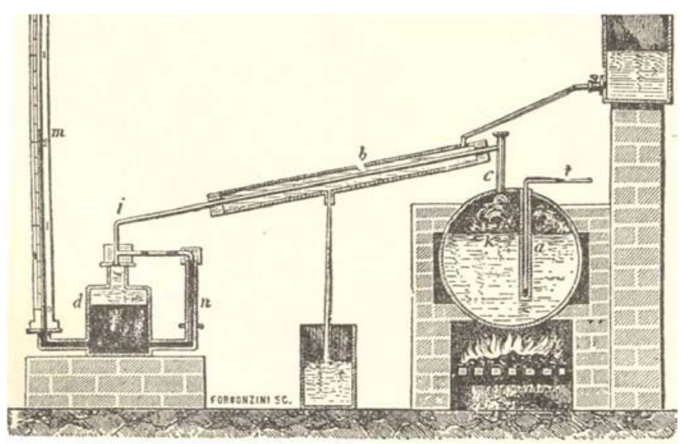


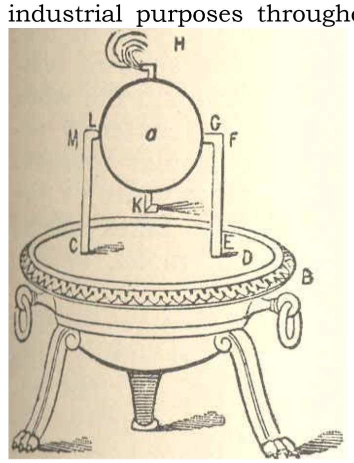
FIG. 2

The Energy of Steam. – Water has the greatest specific heat of any known substance, except hydrogen. By this we mean that more heat enters into it, in order to raise its temperature one degree, than into any other substance, with the one exception mentioned. Its stored energy is 966.6 thermal units per pound, Fahrenheit scale. It is easily condensed, giving out this energy. These facts, together with its universal and abundant presence in large quantities, have rendered steam, up to this time, the means for the generation of mechanical power. The process of changing steam into mechanical, power may be briefly outlined as follows: If we start with water at 32° F. and apply heat, the temperature of the water will rise one degree for each thermal unit, but expansion does not begin until 38 to 40 degrees of temperature are reached. When 180 ½ units of heat have been absorbed the temperature of the water will be found to be 212° F. and its expansive force equal to 14.7 pounds to the square inch, or that of the atmosphere at sea level. At this point the water is incapable of becoming any hotter under that pressure. The heat added, after that point is reached, is used in converting the water into steam, and 966.6 thermal units are required for each pound of water thus converted. This so-called latent heat is stored energy, to be given back again in mechanical work and heat, as the steam is condensed. If we enclose both water and steam in a boiler of suitable construction, and continue heating, part of the water will be vaporized, but being prevented by the envelope of steam from expanding, it crowds the available space, and the pressure upon the surface of the water is increased so that the heat now added increases temperature again. When we have added 1,182 total thermal units (including temperature and latent heat) the pressure, or energy of the steam will be equal to about 100 pounds to the square inch, and the temperature will have risen to 329° F. (see table I., columns 1, 2, and 4).

We have now to consider how this energy is transformed. When the steam in the cylinder of an engine performs work by pushing the piston against a resistance, that work robs the steam of a portion of its heat, hence that steam is condensed. Theoretically, it requires two and a half pounds of steam, saturated, to supply one horse-power of work each hour; but practically, from 5 to 25 times that amount is required to pass through an engine in order to secure this result.
This is due to the loss of the energy of the steam, in giving up its heat to the walls of the cylinder, and to the immense portion of the steam which acts only as backing. In the best quadruple engines of today less than one fifth of the energy of the steam is converted into actual work, and in the best non-condensing engines only one tenth. The waste is enormous, but the abundance of the supply in part compensates for it.

It is estimated that there is 4,000,000 horse-power of steam used in manufacturing in the United States, and that the total horse-power used on an average six hours a day, is not far from 120,000,000. This requires 150,000 tons of steam to be condensed daily. We may safely say that 11 times as much goes to waste, making 1,800,000 tons of steam which passes through our engines daily. A large amount of steam is used, in addition to this, for heating purposes. Its value in this respect is due to its being able to carry more heat for a given weight than any other substance, and when it has given up its heat to drop out of the way, by condensation, and make way for a fresh supply. It is roughly estimated that the amount of steam used in the city of New York alone, for heating purposes, is 18,000,000 tons per year, and in the United States about 10 times as much. It is pertinent to ask what becomes of it ultimately? Nature provides for its absorption in the air, and it is probable that large as it is, it forms but a small fraction of the moisture in the atmosphere. JOHN R. PADDOCK,
Member of the American Association for the Advancement of Science.

Steam and Steam-engines. Steam, the vapor of water, has special interest as the working substance of the steam-engine, the principal source of power for industrial purposes throughout the world, and hitherto, at least, throughout the history of modern industry. Steam is produced in the steam-boiler under constant pressure, that required for the steam engine to which it is accessory and limited by the adjustment of the safety valve. When the feed-water enters the boiler, it promptly passes into circulation and gradually assumes the temperature of the great mass of water of which it forms a part. This rise of temperature is by continuous accession of heat until, the temperature of the steam at the existing pressure being attained, its temperature becomes constant and the inflow of heat takes effect in vaporization, steam being produced in proportion to the heat received. Steam thus produced is said to be "saturated"; if containing no suspended water, as mist, it is "dry and saturated." If, after separation from the water in the boiler, it passes through a "super heater" in which additional heat is imparted, it is said to be superheated, and, behaving as would a gas, it rises in temperature above that due the pressure for saturated steam and its excess of temperature is proportional, very nearly, to the quantity of heat absorbed.



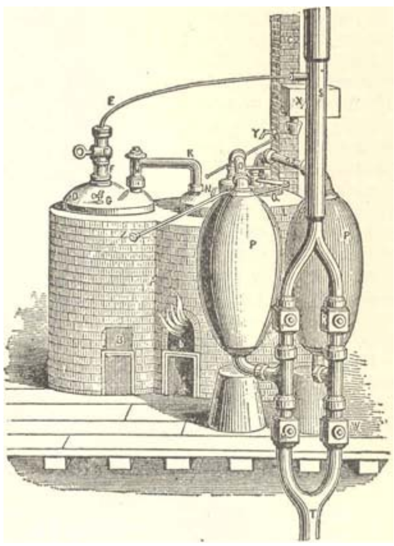
Hero's Steam-turbine (120 B.C.).-A B, steam boiler: CD, supports; a, revolving globe; H K, nozzles.

The existing definite relations between the temperature, pressure, and volume of saturated steam may be expressed with close approximation by simple formulas. Superheated steam may be regarded as a gas, if not too near the temperature of saturation, and these relations may be precisely expressed as with gases in general. The relation of the temperature of water to influx of heat is also definite.

The quantity of heat required to raise unit weight of water through a stated range of temperature, $T_2 - T_1$ is:

$$Q = C\,(T_2 - T_1);\ H = J\,(T_2 - T_1);$$

where expressed in thermal or in dynamic units, *Q* being the thermal and *H* the dynamic measures, and *C* and *J* the thermal and the dynamic measures of the specific heat of the fluid. With water, C = 1 and J = 778 or 427, in British or metric measures, foot-pounds or kilogrammmetres, respectively.



Savery's Engine (1702).- L, boiler; G, feed-vessel; P P, forcing vessels; S, rising main; T, suction

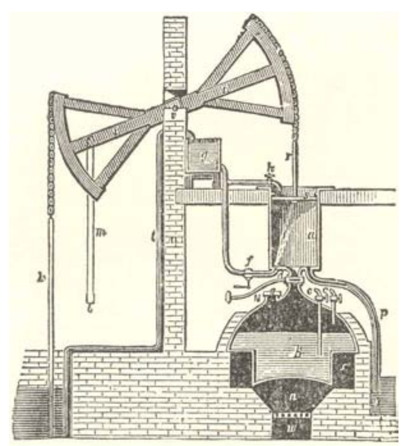
The relation of pressure to temperature of steam in contact with the water from which it is issuing was determined experimentally by Regnault, and the existing tables are founded upon his work. This relation has been expressed algebraically, in empirical and approximate formulas, by a number of authorities. Rankine's formula is log

$$p = 6.1007 - \frac{2732}{T} - \frac{396945}{T^2}$$

the units being pounds on the square inch and temperatures Fahrenheit on the absolute scale. Regnault's formula, with constants corrected by Moritz, is log $p = A + Ba^t - Cb^t$; where for metric measures and for the scale between the freezing and boiling points, A = 4.7393707; log *B* = 8.1319907112 - 10; log *C* = 0.6117407675; log *a* = 0.006864937152; log *b* = 9.996725536856 - 10. Above the boiling point, Regnault gives log $p = A - Ba^x - Cb^x$, in which log *a* = 9.994049292 - 10; log *b* = 9.998343862 - 10; log *A* = 6.2640348; log *B* = 0.1397743; log *C* = 0.6924351. Pressures are in millimetres of mercury; $x = t + 20$, metric.

"Steam-Tables" are given in all treatises on this subject, usually based upon Regnault, and supplemented with columns of data relating temperatures, volumes and pressures to the latent heats. Volumes were determined by Fairbairn and Tait, but are most exactly obtained by thermodynamic computation.

The production of steam in closed chambers involves the expansion of water against external and internal resistances with constant but slight change of volume and with increasing pressure upon the confining walls from minima measured by imperfect vacua to maxima determined by the final temperatures of the steam produced. At the freezing point, this pressure is about 0.006 atmosphere; at the boiling point at the level of the sea, under one atmosphere pressure, the temperature becomes 212° F., 100° C. At pressures employed in the modern steam engine, 6 to 10 and 15 atmospheres, the temperatures rise to from 320° to 356° and 390° F., 160° to 180° and 199° C. Meantime, the volumes of the vapor decrease, relatively to unit volume of water of maximum density, from 1646 at one atmosphere to 300 at 6, to 188 at 10, and to 125 at 15 atmospheres. This change demands the expenditure of energy sufficient to increase the rate of molecular vibration, storing the sensible heat producing the change of temperature and measured by the product of the range of temperature into the specific heat of the fluid, and an amount of energy measured by the product of the change of volume into the external and internal resistances to that expansion, measuring the external and internal, so-called "latent" heats. Sensible and total heats are usually measured from the freezing point. At ten atmospheres, for example, the heat measured, respectively, as sensible, as internal latent and as external latent and as total latent heats, have the relation, very nearly, of one to two and a half, to one fourth, to three and three fourths.



Newcomen's Engine (1705).- *B*, boiler; *a*, steamcylinder; *s r*, piston and rod; *K*, pump rod.

In the production of steam from water at temperatures below the boiling point, three stages may be observed. In the first, the water rises in temperature without sensible change of volume, and substantially all of the heat supplied remains in the form of sensible heat; in the second, the process is one of conversion of the water at the boiling point under the observed maximum pressure, from the liquid to the vaporous state at unchanging temperature, and all heat supplied is converted into the mechanical work of expanding the fluid against internal and external resistances from the volume of the liquid to that of the vapor; in the third, heat added produces "superheat" in raising the temperature above that of the water and steam at the temperature of saturation, converting the vapor into a gas and performing work of expansion if the volume is permitted to increase, or simply raising temperature, and without change from the form of sensible heat, if at constant volume.

The total heat is, in all cases, the sum of that supplied in enlarging the stock of sensible heat and that furnished to perform the work of expansion and thus becoming "latent." Latent heats have the measures: $t = 1091.7 - 0.695\,(t - 32) - 0.000000103\,(t - 39.1)^3$; $lm = 606.5 - 0.695\,tm - 0.000000333\,(tm - 4)^3$; for British and metric measures respectively. The last term may usually be omitted. Total heats have the values, from the freezing point, $h = 1091.7 + 0.305\,(t - 32)$ $hm = 606.5 + 0.305tm$, in the two systems of measurement, respectively. The equivalents of these quantities of heat measure the amounts of mechanical energy expended in steam-making. Superheated steam has a specific heat at customary pressures of 0.4805, the pressure being constant, as is usual in superheating, and this quantity is added with each degree rise in temperature above that of saturation at the same pressure.

In all cases, the heat and the equivalent energy required are measured by the sum of that needed to produce the observed change of temperature and that required to perform the work of expansion against internal and external resistances as measured by the molecular cohesion and the pressure on the confining walls of the chamber in which the process takes place, whether the steam be saturated, moist, or superheated.

Algebraically, $H = H_1 + H_2 + pdv$; where H is the total heat, H_1, that present at the initiation of the change observed, H_2, that required to increase temperature and p and v the mean pressure and resultant change of volume; all energy being here measured in dynamic terms, foot-pounds or kilogrammeters.

Where the steam is wet, the heat and energy demanded in such changes are measured by the sum of that absorbed by the water present and that taken up by the steam. If x be the proportion of steam in the mixture, the latent heat becomes, per unit weight of mixture $lx = xl$; the total heat will be $hx = h + xl$; and the total volume will be very nearly xv, that of the fraction of steam present, v, h and l being the specific volume, total heat of water and latent heat of steam, per unit of weight, at the observed temperature.

For superheated steam, $pv = aT$; p, v and T being respectively, the pressure, specific volume and absolute temperature.

The heat stored in steam and available in the production of work by expansion, as in a steam-boiler explosion, was first computed by Airy, later more accurately by Rankine. The latter gave approximate expressions thus:

$$U = \frac{J(T-212)^2}{T+1134.4};\quad Um = \frac{J(T-100)^2}{T+648}$$

for British and metric measures, respectively; energy being expressed in foot-pounds and kilogrammetres and temperatures in Fahrenheit and Centigrade. J is the mechanical equivalent of heat. in foot-pounds or in kilogrammetres.

The quantity of this stored energy is thus found to be enormous. At 10 atmospheres pressure, the energy thus liberated by one pound of water released from under that pressure would be above 10,000 foot-pounds, and one pound of steam would give over 125,000 foot-pounds. The total energy stored in the steam boiler is contained in a large weight of water and a comparatively insignificant quantity of steam; thus it happens that the danger to life and property when a boiler explodes is greatest where the boiler contains most water. In the common cylindrical fire-tube boiler, of 1,000 square feet heating surface, these quantities may be, respectively, 60,000,000 foot-pounds and 1,200,000, sufficient to raise the boiler itself a mile high, in the one case, and about 1,000 feet in the other. The locomotive often stores twice these amounts of energy in destructive form, and the larger water-tube boiler about two thirds as much as the standard fire-tube boiler, per unit of rated power.

At usual pressures, the quantity of heat stored in steam, available and unavailable, is about the equivalent of two and a quarter pounds per horse-power-hour, or very nearly a kilogram. This would be the consumption of steam by an ideally perfect engine, operating with an efficiency of unity. The most economical steam engines the world has produced approximate 25 per cent thermodynamic efficiency and demand about 10 pounds of steam per horse-power-hour, or nearly five kilograms.

Steam-engines and Boilers constitute the apparatus by means of which the stored heat energy of fuel, transferred to water and steam, is transformed into mechanical work. This transformation of thermal into dynamic energy, this thermodynamic change, requires for its successful and economical conduct special forms of mechanism and is subject to a variety of wastes of serious aggregate amount, even with the most perfect of modern engines. The series of processes in the train between the fuel and the point of application of the useful energy with statement of the corresponding wastes and efficiencies are as follow; it being understood that an efficiency is the quotient of useful result divided by outgo producing it, the two being expressed in similar terms: These efficiencies are those of

1. Combustion of fuel; ratio of heat set free to total heat latent in the fuel. This efficiency is usually not far from 0.90. Wastes due to incomplete combustion.

2. Heat-transfer from furnace to boiler; efficiency, as a rule, about 0.75, as measured by heat stored in the steam supplied. Wastes occurring mainly at the chimney.

3. Heat-transfer from boiler to engine with loss by conduction and radiation, en route. Efficiency of operation about 0.90 in small boilers and increasing to 0.95 or 0.98 in large sizes.

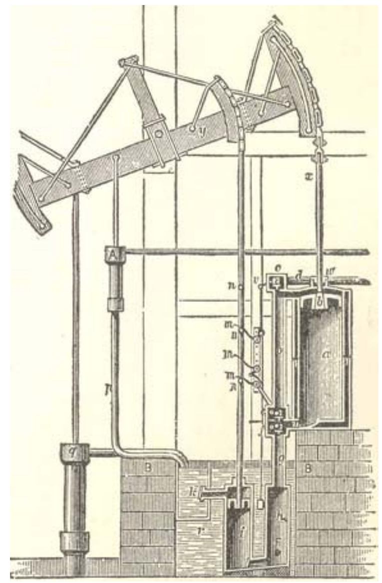
4. Heat-transformation into work at the engine with wastes by defective thermodynamic change and rejection of heat at the lower limit by conduction and radiation within and without the cylinder, variable with size, with mean temperature of steam and other conditions. Efficiencies for the ideal case usually approximate 0.25 with only thermodynamic wastes, and attain to 0.20 with successful constructions in the real case; the wastes including the thermodynamic and inevitable losses and the partly controllable extra-thermodynamic wastes.

5. The transfer of mechanical energy from cylinder to point of application. The wastes occur by friction and usually amount to about 0.10, as a minimum in condensing, and to 0.05 in non-condensing engines. Efficiency, 0.90 to 0.95.

The thermodynamic efficiency of the best steam-engines may be thus taken to be 0.25; the thermal efficiency at the engine, involving other wastes than thermodynamic, about 0.20; the total efficiency between steam-valve and fly wheel about 0.18 and the efficiency of engine and boiler combined not far from 0.14; while the total efficiency of engine, boiler, and furnace, from coal-pile to engine-belt, may be about 0.125. In common constructions these efficiencies are much reduced and in many cases may be divided, by from two to four, the demand for fuel of good quality ranging from about one pound or half a kilogram in the best work to several times that amount per horse-power-hour, and for steam from ten pounds, about four and a half kilograms, to a multiple of that quantity. In some instances, as with many small boiler feed-pumps, 10 or even 20 times the minimum figures just given are reached, the wastes becoming enormous and the utilized energy of the fuel insignificant.

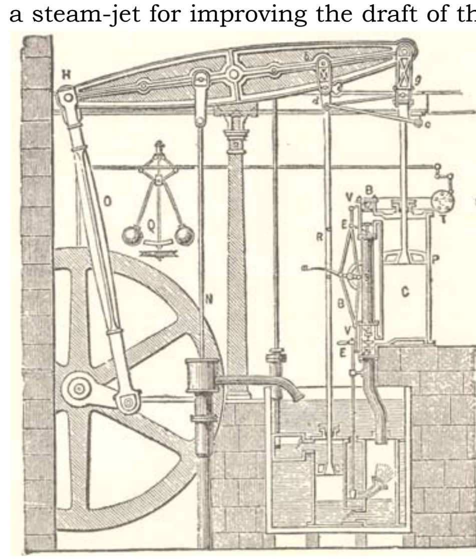
The "ideal case" is understood to be that purely thermodynamic operation which illustrates the conversion of thermal into dynamic energy where no other energies than thermal and dynamic are concerned, and where the change is effected in a machine which is not subject to wastes by conduction or radiation; an apparatus composed of perfectly non-conducting materials and perfectly constructed. In the "real case," the materials of construction are necessarily good conductors and good radiators of heat, and the wastes by conduction and radiation are often supplemented by leakage of steam as well as of heat. In the real case, the details of construction, adjustment and operation affect very greatly the resultant efficiency and the commercial rating of the engine. The study of the steam-engine thus comprehends the ideal, the purely thermodynamic, case and the real case with its various wastes, thermodynamic and extra-thermodynamic, as well as an investigation of the principles and practice in the design and construction of the real engine.

Engines. – The power of steam and the employment of that fluid in various sorts of engines have been familiar to mankind from an unknown and possibly prehistoric period. The earliest known record is that of Hero, who, in his "Pneumatica," of which the manuscript was produced at Alexandria, about 120 B.C., described a steam-turbine and several forms of steam-fountains and steam-boilers. So far as known, none of them had any useful application and they were simply toys or impracticable schemes. It is unknown, in fact, whether any of them were constructed; although the drawings appear in some cases to be those of actual constructions.



Watt's Engine (1774). – *a*, cylinder; *b*, piston; *x*, rod; *y*, beam; *i j*, air-pump and condenser; *m*, valve-gear.

Through the later centuries, up to the 17th, but little progress was made either in the acquirement of a knowledge of the properties of steam or in its application to useful purposes. Some forms of "æolipile," furnished a steam-jet for improving the draft of the chim-



Watt's Double-acting Engine (1784).- C, cylinder; *b*, beam; O, connecting rod; Q s, governor and valve.

ney, apparatus for turning the spit and even more ambitious uses were either attempted or suggested; but, until Da Porta's treatise on pneumatics appeared in

1601, in which a steam-fountain was described, and the description in 1629 of an impulse steam-turbine, by Branca, no development took place of any real importance. It was not until the second Marquis of Worcester, Edward Somerset, constructed a steam-fountain (1650) and employed it in raising water from the moat to the top of the tower of Raglan Castle, and later erected another for similar purposes at Vauxhall, that the story of the evolution of the steam-engine really begins. Meantime the scientific men of the later centuries were acquiring some exact knowledge of the nature of steam, earlier confounded with other gases, and some familiarity with its latent powers.

Steam power first became an acknowledged industrial agent and useful as a prime mover when Savery, at the beginning of the 18th century (1698), made Worcester's steam-fountain practically applicable to the drainage of mines and the elevation of water for water supply generally. This apparatus, which could not be properly called an engine, consisted of a pair of cylindrical or ellipsoidal “forcing vessels” which were alternately filled with water, by the production of a vacuum within the vessel, and emptied by the introduction of high-pressure steam from an adjacent boiler; the one being emptied while the other was filling and vice versa. This apparatus, introduced by Savery, improved and further made known by Desaguliers and by Smeaton, was known and in use before the year 1775 throughout the world where mining at considerable depths and in presence of water was carried on. The steam-fountain is still in use and is known as the “pulsometer".

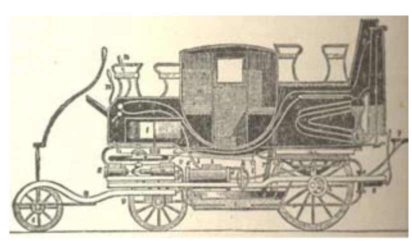
Newcomen's steam-engine, the first steam engine properly so termed, the first which consisted of a train of mechanism as distinguished from the Hero steam-fountain, which was a piece of apparatus without moving parts. was patented in l705. It consisted of a steam-cylinder and piston, actuating a beam, above, from the opposite end of which was pendant the pump-rod operating the pumps in the shaft of the mine. It was always used as a steam pumping engine. Thomas Newcomen and his partner. John Calley, are thus to be credited with the invention and introduction of the modern steam-engine with all its essential elements as a pumping engine. It was the improvement of this engine by the addition of various valuable devices which gave James Watt his fame and fortune.

This earliest type was a condensing engine in which condensation was effected by means of a jet of water directed into the steam cylinder when the pressure on the under side of the piston was to be removed. The upper side was open to the air, there being no upper cylinder head. The engine was thus operated by the atmospheric pressure, steam being held at about atmospheric pressure and only employed to secure a vacuum below the piston. The pressure of the atmosphere depressing the piston, the pump-rod on the opposite end of the beam was raised and the pump filled. With the fall of the pump-rod the water was forced out of the pump and raised to the upper level. The weight on the outer end of the beam always overbalanced the weight of the piston and attachments sufficiently to do the required work. This type of engine remained in use for a century, and old engines of Newcomen's time are still in existence. The type became known later as the Cornish engine, Watt's improvements having been meantime added. After Newcomen's death, the machine was improved in details by Desguliers and by Smeaton, who considerably increased its economy by attaching wood to the piston and cylinder-head to prevent what had been called “cylinder condensation” by action of alternately heated and cooled metal in contact with the steam. This was probably the first recognition in construction of this important phenomenon.

The valves of this engine were at first worked by hand; but a boy, Humphrey Potter, is credited with having devised an automatic system, which, later in 1718, carefully designed and constructed in a workmanlike manner by Henry Beighton, a well-known engineer of that period, became the first automatic valve-motion.

James Watt, introducing the needed improvements in the Newcomen engine, finally produced the modern types of “reciprocating” steam-engine. His first great improvement was the separate condenser, which permitted condensation to be effected without the introduction of water into the working cylinder and thus reduced very greatly the waste of steam by initial condensation. Watt first enunciated the principle: “Keep the cylinder, if possible, as hot as the steam that enters it.” The first step was this of removing the primary cause of refrigeration. The next was to surround the cylinder with a chamber containing steam at boiler pressure; thus introducing his second great invention, the “steam-jacket.” He next covered the upper end of the cylinder, excluding the cold air and supplying the place of the atmosphere and its pressure on the upper side of the piston by steam from the boiler, completing his scheme of keeping the cylinder as far as was practicable as hot as the entering steam.

The “double-acting engine” constituted the next and an easy step. With steam admitted at both ends of the cylinder, it was immediately evident that each might be utilized, alternately, in the performance of work and Watt soon adjusted his valve-gear and connections in such manner as to permit this alternation and produce a push and a pull on the piston-rod. This compelled a rigid connection between the piston and overhead beam, on the one end, and between the outer end of the beam and its work, now become that of rotating a shaft with crank and fly-wheel. Thus one improvement led to another and Watt's steam-engine



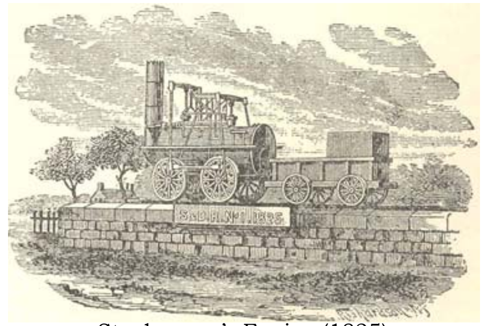
Gurney’s Steam-carriage (1828)

ultimately became capable of supplying power to every imaginable kind of machine or work. The single-acting engine was, for many years after Watt's death, used in raising water and the double-acting engine continues to turn the shaft of mill, locomotive, steamship and factory.

Watt Invented and introduced many accessory inventions and devices, as the attachment of the governor – already a well-known apparatus the steam-engine "indicator," the expansion of steam, the compound engine, the non-condensing engine, practically all that distinguishes the modern engine from that of Newcomen. These improvements raised the "duty" of the pumping engine, in the course of 25 years, from about 7,000,000 foot-pounds to 30,000,000, and, in the latest forms of Cornish engines, about 1850, to twice the last figure or more, reducing cost of steam-power enormously, and at the same time adapting the steam-engine to every requirement in the industries, giving to the world, in fact, its contemporary civilization. This cost in coal per horse-power-hour is reduced from the 35 pounds of Smeaton's time to one pound, as a minimum today, and the work of the world is performed by steam-engines, mainly, probably amounting to 150,000,000 horsepower and equivalent to the working power of several times the population of the globe, if employed in manual labor.

At the commencement of the 19th century, Trevethick and other able mechanics and inventors were seeking to construct locomotives, and complete success was achieved by George Stephenson in engines built from 1814 to 1833. The steamboat had been suggested by numerous writers and engineers, and, after many attempts, was made a practical success by John Fitch in the United States about 1785, by John Stevens in 1804-9 and commercially by Fulton, 1807-15. In Great Britain, after many early failures, Miller and Symmington and Bell, step by step, attained permanent success and by 1830, the date of the first transatlantic steamship voyages, those of the Cirius and the Great Western, all civilized countries were employing the steamboat. See STEAM VESSELS.

Meanwhile the elements of economy became recognized and steam-pressures rose from the two to seven pounds above the atmosphere of Watt's time to 25 or 30, about 1850, and to 100 and upward to occasionally 200 at the end of the 19th century; the ratio of expansion of the steam increasing in similar ratio. The speeds of engine-piston also gradually increased from about 100 feet per minute, at the beginning, to 600 and often to 1,000 at its end. The weights of engine and sizes for the usual powers meantime fell from 1,000 pounds or more per horsepower developed at the time of Watt, 500 about 1850 and to 250 in 1900 where weights were comparatively unimportant and, in special cases, where weight and volume required to be reduced to the smallest possible figures, as for torpedo boats, to a fourth or a fifth, the last named quantity; while, in aeronautic work, ten pounds per actual horse-power has been reached and still lower figures are considered probable in the near future.



Stephenson's Engine (1825)

The compound, the triple and the quadruple expansion engine have largely displaced the simple engine of Watt; the first of these types having been introduced in Watt's time by Hornblower, Woolf and Falk and the second by Kirk about 1874; while the last-mentioned became standard with the rise of steam-pressures to about 15 atmospheres, about 1890. These complications are mainly the outcome of the endeavor to follow Watt in repressing the waste by cylinder condensation, reducing the proportion of heat-absorbing surface and the temperature-head producing flow of heat into the metal of the cylinder. Incidentally, the multiple cylinder engine gives a steadier rotation of the crank-shaft and a smoother action of the steam than the simple engine, and also reduces weight by lessening the maximum load upon the working parts, the range of pressure in each cylinder being reduced with this reduction of temperature-range.

This steady progression from the days of Watt to the end of the 19th century finally culminated in a retrogression to the simple form of the Hero engine, the steam-turbine, in which all the complication of the Watt-Newcomen engine is done away with and but one moving part performs every essential office, apart from condensation, and yet secures, in its best constructions, the economical results of the whole series of changes distinguishing the 19th century, with the added gain of reduced volume, weight and cost, both initial and operative. The turbine promises thus to provide power with maximum ultimate result in financial efficiency. Meantime, the gas-engine, after a similar period of development, is now rivaling the reciprocating steam-engine in many of its fields. The best steam-engines of both the standard types and the gas-engine are now capable of deriving large powers from substantially the same quantity of energy potential in fuel.

The Structure of the Steam-engine differs in detail according to place and purpose. The familiar forms may be thus classed: A primary classification as condensing and non-condensing distinguishes engines by their utilization or non-utilization of the vacuum. In the former class, condensation may be effected by surface or by jet-condensation; this distinction indicating a subordinate method of identification of a variation within the type. The usual classifications are based upon the essential features of structure, and these are ordinarily as follows:

1. According to the number of cylinders.
    (1) Single cylinder, simple engines.
    (2) Multiple cylinder engines, "compound," etc.
2. With reference to the construction of cylinders:
    (1) Fixed cylinder.
    (2) Movable cylinder.
3. In the first case, the engines are:
    (a) Vertical.
    (b) Horizontal.
    (c) Inclined.
4. In the second case, they. are:
    (a) Oscillating, vibrating, etc.
    (b) Rotary, steam-turbines.
5. With reference to the action of the steam:
    (1) Single-acting.
    (2) Double-acting.
6. With reference to the transmission of the steam power:
    (1) Direct-acting.
    (2) Indirect-acting.
7. And in the latter case either
    (a) With balance lever, or beam.
    (b) Without lever or working beam, geared, etc.

The essential details of these engines are usually the same in all the forms in which the individual piece is found. A rod or a crank, a shaft or a valve, will commonly be found to have assumed a standard form, and the differences in engines is largely a difference in grouping. Since Watt, but few advances have been made in real invention, and the progress observed has been mainly one of refinement and adaptation. Frederick E. Sickels introduced a successful form of "drop cut-off"; Corliss, Greene and others invented improved valve-gears embodying the same general principles, and Porter and Allen, and others, successfully established the "high-speed" engine as a motor where rapid rotation of the prime mover facilitated transmission of power, as with electric generators and on rolling mills.

Similarly, the locomotive proposed by a number of earlier inventors, particularly by Trevethick, who constructed several, was successfully brought into use by George Stephenson and, today, in its many forms and uses, the engine in its essential details and distinguishing feature is that of Stephenson, refined and adapted to high and to low speeds, to heavy and to light loads. A very noticeable feature of the later engines is the forward "truck" or "bogie," devised by John B. Jervis, which, by permitting the forward wheels to swivel and the engine to rock upon the truck, accommodates the locomotive to sharp curves and irregular track.

In marine construction, a similar adaptation of the form and proportions of the engine to the special purpose in view gives rise to the types employed with side-wheel and screw, high powers and low, to the essential requirements in lightness and small bulk of torpedo-boat practice and the needs of transatlantic navigation and of that of the rivers of the United States. The substitution of surface condensation for condensation by the jet has been compelled in seagoing ships by the use of high-pressure steam and the impracticability of using sea-water in the boilers. The later forms of engine are thus refinements and adaptations of the earlier.

Meantime, in all directions, the steam-engine has come to be utilized in the production of very large powers, and its construction in very large units is found to be very frequently economically desirable. Stationary engines for mills, and especially for large power-stations supplying the energy applied in electric lighting or power distribution for electric railways, are built in sizes ranging from a few hundred horse-power to five and even ten thousand horse power, and sometimes grouped into systems rating as high as 100,000. Marine engines are also constructed in these large sizes and powers, and as high as 50,000 horse-power may be needed for the latest and largest transatlantic steamer. The locomotive, in the time of Stephenson weighing, in the case of his first successful machines, four to six tons is now built of above 100 tons weight and capable of hauling loads of 5,000 tons at good speeds, on level rails. The steam pumping engine of the time of Newcomen and Watt had a capacity of a few hundred thousand gallons per day; it is now furnished in sizes up to 20,000,000 and 30,000,000; while its duty has risen from the comparatively insignificant figures of the times of the inventors to 150,000,000 and 160,000,000 foot-pounds per hundred pounds of fuel. The steam-turbine for all these uses, may now be obtained in as large powers as the reciprocating engine and with substantially the same guaranteed duty. Its relatively high speed of rotation, ranging from 600 to 1,000 in the largest sizes, to 10,000 or more In the small, and its smooth rotation, make its use distinctively advantageous in electric services and its small weight and volume are peculiarly helpful to the marine engineer and naval constructor.

The Thermodynamics of the Steam-engine the science of its ideal case, involves the fundamental principles of Energetics, and in particular the laws governing the transformation of energy from the form of heat to that of mechanical energy and vice versa. An all-comprehending law, of which the laws of energetics are in fact corollaries, the law of Existence, or of Persistence, is expressed thus: All that exists, whether matter or force or their resultant, energy, and in whatever form, is indestructible by finite power.

Matter may change its form and its chemical composition by rearrangement of its molecules or of its elementary atoms, but it cannot be destroyed; forces inhere and are persistent as characteristics of all matter and cannot be separated therefrom; energy, like matter, is constant in its total quantity in the universe and may be transferred and transformed, but cannot be extinguished. Transformation of energy, as of thermal into dynamic or mechanical, is simply the change of the kind of mass affected and consequent alteration of the kind of motion due to its action. A shot from a gun, stopped in its rapid flight by impact on the target, if not fractured, will exchange the thousands of foot-tons of mechanical energy sustaining its flight for precisely the same quantity of molecular motion and energy. Similarly, were a shot heated to a high temperature and then were all its molecules by some conceivable process of steering each into its path, made to take up simultaneously a definite rectilinear motion, it would become absolutely cold and would fly out into space with a dynamic mass-energy precisely equal and, in fact, with the identical energy at first displayed as molecular. The heat-engine is a device for bringing about such a change for industrial purposes.

The laws of energetics, as usually enunciated, are:

1. The Law of Persistence, or of Conservation of Energy, namely: Existing energy can never be annihilated; and the total energy, actual and potential, of any isolated system can never change.

This is evidently a corollary of that grander law, asserting the indestructibility of all the work of creation, which has already been enunciated.

2. The Law of Dissipation, or of Degradation of Energy, namely: All energy tends to diffuse itself throughout space, with a continual loss of intensity, with what seems, now, to be the inevitable result of complete and uniform dispersion throughout the universe, and consequently of entire loss of availability.

It is only by differences in the intensity of energy, and the consequent tendency to forcible dispersion, that it is possible to make it available in the production of work.

3. The Law of Transformation of Energy, namely: Energy may be transformed from one condition to another, or from anyone kind or state to any other; changing from mass-energy to molecular energy of any kind, or from one form of molecular energy to another, with a definite quantivalence.

Thermodynamics, being a restricted energetic, in which only two energies, thermal and dynamic, are comprehended, its laws are, fundamentally, identical with the preceding and the enunciation just adopted is entirely accurate in this restricted science.

The Laws of Thermodynamics, in the special forms considered best for the purposes of the thermodynamist, are corollaries of the laws of energetics and of Newton's laws, which are a different method of expression of the same fundamental principles. They are usually stated thus:

1. Thermal and Mechanical Energy are mutually interconvertible in the proportion of one British Thermal Unit for each 778 foot-pounds, or of one calorie for each 427 kilogrammetres of energy or of work.

The mechanical equivalent of heat is the specific heat of water at its temperature of maximum density expressed in dynamic units, as foot pounds or kilogrammetres.

The value, of the mechanical equivalent of heat has been taken as first adopted by Joule, although recent and most carefully conducted investigations indicate a value higher, by perhaps one per cent, to be more accurate. Many existing tables, and much work done in this field to date, have, however, been based upon Joule's figure, 772 foot pounds, 423 kilogrammetres. The figure, above given, 778 or 427, is now, however generally accepted.

2. *The total of any single effect of any given quantity of heat acting in any thermodynamic operation is proportional to the total amount of heat-energy so acting.*

This principle is substantially that first accepted by Rankine as the second law. Actual energy of vibration is understood.

Thus, of the whole quantity of heat passing from the heater to the working substance, one part is always transmuted into mechanical work, or energy; while the remainder goes to the refrigerator, and the ratio of the one quantity to the other is perfectly definite.

Professor Wood expresses this law thus:

"If all the heat absorbed be at one temperature, and that rejected be at one lower temperature, then will the heat which is transmuted into work be to the entire heat absorbed in the same ratio as the difference between the absolute temperatures of source and refrigerator is to the absolute temperature of the source."

The second law finds important application simply in enabling us to ascertain the total quantity of work, external and internal, required to produce changes of volume and energy in fluids, like the vapors, in which we cannot measure directly the internal forces and internal work.

If the change of sensible heat be called dS, that of "latent" heat, dL, and of external work dU, then the first law of thermodynamics is expressed by the equations:

$$dH = dS + dL + dU, \qquad \text{(A)}$$

and

$$dH = dS + dW, \qquad \text{(B)}$$

$$dH = dE + dU, \qquad \text{(C)}$$

where, in the last two expressions, $dE=dS+dL$, and is the variation of energy actual and potential; while $dW=dL+dU$, and is the total work done, externally and internally. These are primary and general equations.

The quantity E is often called the intrinsic energy of the substance; L is evidently a potential energy; while S is a form of molecular kinetic, or actual, energy, which may sometimes be regarded as also in a sense potential.

The above are completely general expressions of the *general fundamental equation of thermodynamics.*

Internal work or energy, positive or negative, is the work performed in changing the relative distances between molecules, atoms or corpuscles, or in causing variation of their relative velocities, and within the mass and out of reach of the human senses. In the fundamental equation, it is measured by dL.

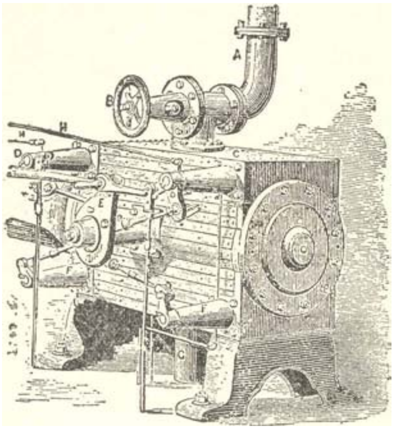
External work is that performed by mass or molecule, by atom or corpuscle against outside resistances, as where steam expands, doing work upon a piston. As indicated by the above laws, it must do so by surrendering an equivalent quantity of heat-energy. This is dW.

Heat-energy, thermal or dynamic, is of the same nature and may be measured in either thermal or dynamic units, foot-pounds and kilogrammetres, or in British or metric thermal units or "calories." One *B.T.U.*, expressed in thermal units, is 778 foot-pounds expressed in dynamic units; one metric unit, the calorie, is 3.96832 times as great as the British, or the *B.T.U.* is 0.251996 of the metric unit. The engineer often conducts his thermoydyamic investigations in dynamic terms; the physicist and the chemist employ the thermal; the one often uses British, the other always adopts the metric.

Where work is performed by an expanding fluid upon a moving piston, the total work,

$$U = (Pe + Pi)\ as;$$

where a is the piston-area, and s is the space traversed by the piston; mean pressures corresponding to the external and the internal work being Pe and Pi while $as=v$, the volume traversed.



Corliss Engine Valve-motion (1850)

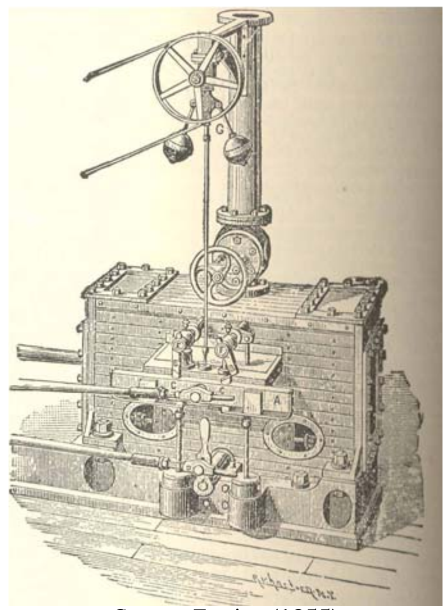
The Perfect Gas is a fluid within which no internal work is done with varying volumes and which may be defined by the equations, $pv = aT$; $pv / T = a$. In thermodynamic equations, the perfect gas has zero values of internal energy and work. T is absolute temperature, p and v the pressures and volumes at that temperature of unit mass.

Vapors are fluids in which the internal energy and work may be large, both absolutely and relatively, with changing volumes. Internal cohesive forces are often not only sensible but very great, the internal latent heat, which simply measures the internal work, when expanding water into vapor of one atmosphere pressure, as an example, is the equivalent of the work of elevation of the weight affected 'to a height of .about 150 miles. These forces, however, as with the gases, do not prevent the free movement of molecules in any direction and to any extent; nor do they fix the volume and density of the substance.

Liquids are fluids in which the action of internal molecular forces gives stability of volume, but not of form, and the energies, internal and external, are thus limited to comparatively small ranges and to comparatively small values; while range and values are often enormously great when the liquid becomes vaporous, not withstanding rapid diminution of molecular attractions.

Solids have stability, both of volume and of form; the ranges of internal forces and of energies are still more restricted than with liquids and their extent of action and their values are still less than in liquids. By accession of heat, all solids become at some definite point liquid, liquids become vapors and vapors, when "super heated," become gases. It is to be noted that, whenever a substance, of whatever class, alternately expands and contracts through a fixed range of volume, whatever its temperature or the pressure, precisely the same amount of internal energy is lost and gained by variation of volume against or with the constant effort of the internal forces.

Cycle is, thermodynamically, an operation in which a working substance passes through a series of changes of pressure, volume and temperature resulting in the final return of the substance to its initial physical state. In this operation, it is evident that the net change of internal energy is zero. This process is illustrated in heat-engines in which the working substance is confined within the working chamber and therein passes through repeated cycles with repetition of the kinematic cycle of the machine itself. Obviously, also, where a working fluid traverses a cycle, the presence or the absence of the quantity of internal energy becomes a matter of no importance when we seek only to determine the quantity of permanent thermodynamic transformation. The magnitude and effect of internal forces and energies have no Influence upon the efficiency of transformation; but they have impor-



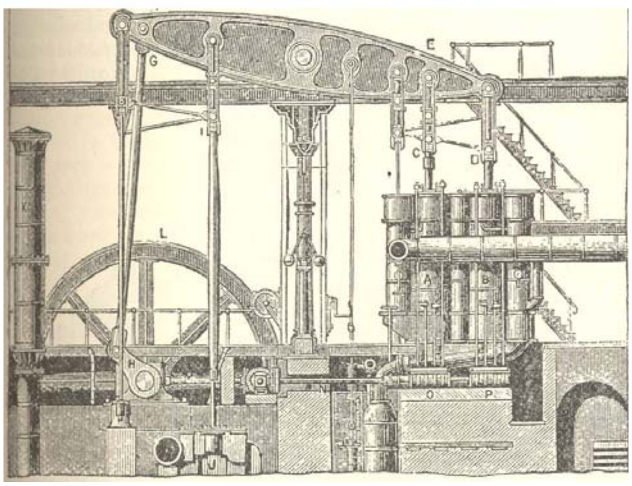
Greene Engine (1855)

tance as affecting the relations of pressure, volume and temperature and the magnitude of the working cylinder and of the heat-engine itself. A steam, or other vapor, engine is vastly more compact than a gas-engine operating under similar thermal conditions, under similar limiting external pressures. The internal forces affecting water and its vapor are large and confine the substance, at any stated temperature, to small volume and give it a high density, relatively to its gas. In the highest boiler pressures now usual, these forces are about ten times the gauge pressure. At atmospheric external pressure, they amount to thirteen atmospheres. These pressures cannot be measured by any gauge, but may be readily computed with precision from easily ascertainable data; they are perfectly well known, as are the specific volumes of the fluid, which are very difficult, but not impossible, of direct measurement.

The gas-engine has the advantage, in comparison with the steam-engine, in its higher available temperature range and consequent higher thermodynamic efficiency.

The exact treatment of the thermodynamics of the steam-engine requires the use of the higher mathematics, but the general principles have been given and the following will permit its applications to be understood:

A steam-engine is a thermodynamic system in which only thermal and dynamic energies are present and operative. Its action is to transform as large a proportion as possible of the heat supplied it into mechanical power and work. Each pound of steam from the boiler usually brings over the equivalent of about 0.4 horse-power-hour and each horse-power-hour is the ideal equivalent of the heat-content of about 2.3 pounds, a kilogram, nearly, of boiler steam. Of this heat, a part, which is precisely measured by the area of the indicator diagram, is converted into useful work and an "efficiency" is attained measured by the ratio of the useful to the supplied energy in common units. Thus: where 23 pounds of steam per hour are demanded per horse-power developed, in the case assumed, the efficiency is 10 per cent; the heat supplied



Double Cylinder Pumping Engine (1878)

being that furnished from the fuel and measured by the difference between the "total heat") of the feed-water at condenser temperature and that of the steam in the boiler.

The nine tenths which fails of utilization is composed of a variety of wastes, including the thermodynamic, that portion of the heat reaching the steam-cylinder and actually acting upon the piston which is not converted into indicated work, the waste by conduction and radiation externally, and the waste by the transfer of heat between the metal of the cylinder and the working fluid. These quantities in a good example may be taken as follows, the friction wastes of the machine itself being included:

Available heat-energy from the boiler 100	Thermodynamic wastes	70
	Internal thermal loss	10
	External waste	5
	Friction	2
	Useful Work	13
		100

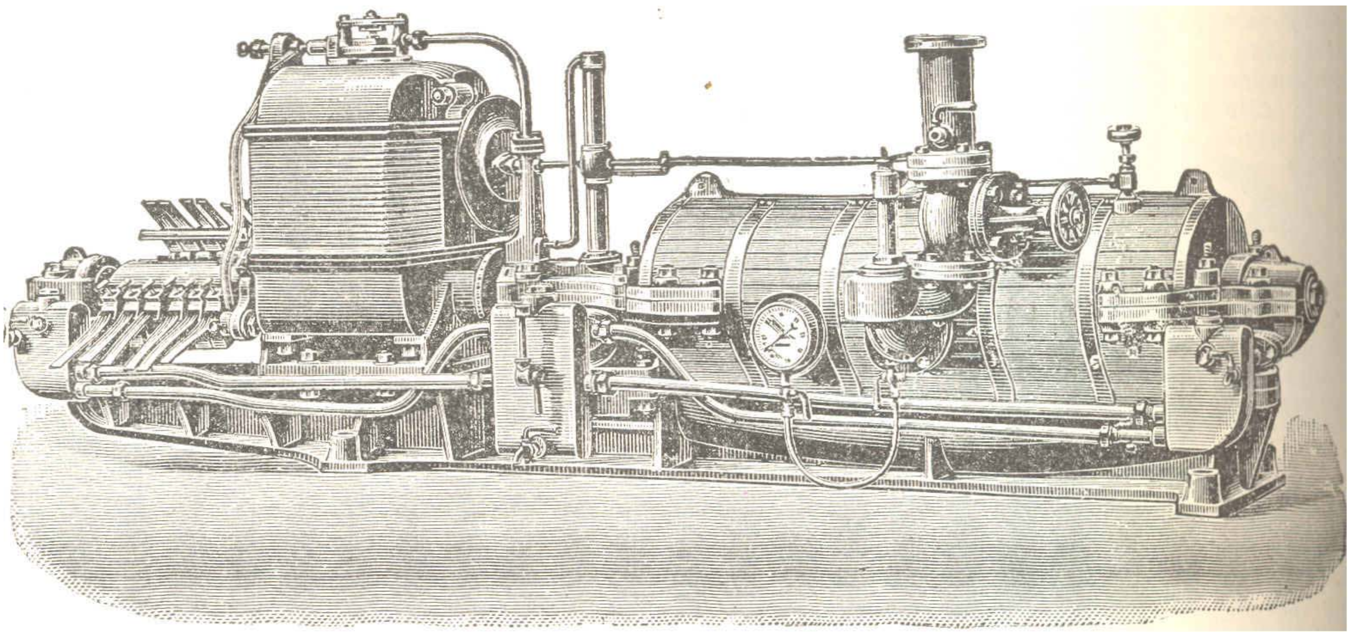
This corresponds, for the ideal case, to an efficiency of 0.20, nearly. The external waste of the steam-engine is usually considered to be covered by an allowance of about one *B.T.U.* per square foot per hour per degree range of temperature, Fahrenheit, or about three calories per square metre, although, on exposed metal having a rough surface, it may attain two to three times these figures. The exterior of the cylinder is commonly lagged and the heads, if not thus covered, are polished, thus minimizing the waste. The total waste, on even small engines, has been found capable of being reduced to less than 3.5 per cent, total, inclusive of engine and boiler, by the use of good non-conducting coverings. This loss is often quite unimportant on large engines.

The internal wastes are produced by heat-exchanges between metal and steam, at induction and eduction; the steam giving heat to the metal at its entrance into the cylinder and robbing the metal at exhaust, thus transferring heat often in large quantities from the steam to the exhaust side, very much as leakage carries the steam itself with its charge of heat. The effect on efficiency is precisely that of leakage. In this action, the cylinder-heads and the sides of the piston, being exposed to the widest range of temperature and for the longest periods, are most fruitful of waste; the cylinder, proper, and especially its middle portion, wastes least. The total loss is a function of the temperature range, the time of exposure to transfer, and the quality of steam, and of the ratio of expansion which measures rudely the quantity of steam per unit weight of metal. In anyone engine it may be stated, as a rough approximation, that the condensation is a constant quantity at all expansions. It may be treated as either a constant leakage or as a constant loss of work measurable by an equivalent back-pressure. A common value of this leakage may be taken, in pounds, as not far from 0.02 *B.T.U.*, per square foot of surface exposed at cut-off, per minute per Fahrenheit degree of temperature range. As a fraction of the steam supplied, it is approximately proportional in any given engine to the square root of the ratio of expansion. With various types of engine, it ranges from 25 or 30 per cent, with simple engines of moderate size to 10 per cent, in multiple-cylinder engines of modern construction as a minimum. In steam pumps and very small engines, it may amount to more than the whole amount of steam taken in, for thermodynamic action. These machines, demanding 100, and even sometimes I50 or more pounds of steam per h.p.hr., waste three fourths or more by "leakage" of heat. The "record-breaking" engines of large size and superior design demand as little as 10 to 12 pounds, approximating 200 *B.T.U.* per h.p.hr.

The velocity of heat-exchange in this manner is many times greater than in transfers across the boiler heating surfaces. It is the most rapid known form of condensation of steam, and is often 10 times as rapid as the production of steam in the boiler supplying it.

The conditions of maximum efficiency are mainly two: the reduction to the practicable minimum of the thermodynamic waste by increasing in all possible ways the area of the indicator diagram per unit of steam supplied, and by minimizing the wastes of heat between boiler and engine-piston. The first includes the increase of the initial pressure, with decrease of back-pressure and adjustment of the ratio of expansion of the steam to the range thus secured; the second involves reduction of conduction and radiation by use of suitable non-conducting coverings of heated surfaces, protection from cooling influences and reducing "cylinder condensation" by drying and superheating the steam, by increasing the speed of engine and by diminishing the heat-exchanges between metal and steam by fine finish of surfaces, and, where practicable, by interposition of non-conducting material, as was done by Smeaton and attempted by later inventors.

"Mechanical efficiency," the ratio of work transmitted from the piston to the point of useful application, ranges from 95 per cent in direct-acting engines as a maximum, to 85 per cent with the older non-condensing engines. It is made a maximum and friction reduced to a minimum by careful design, and especially by securing constant, complete and free lubrication; usually, in the best cases, by a circulatory flow of oil, flooding the bearings and returned by pumps to the source, through a filter, to be again distributed to the rubbing surfaces of the engine. The lost work is the less, as the pressures are higher within limits determined by the nature of the materials as the lubricant is better adapted to its intended purpose, and as the flow is more liberal where reaching the rubbing parts. The highest values of the coefficient of friction are often ten and sometimes twenty times the lowest and the careful attention of the engineer to this detail is always well compensated.



Parson's Steam-Turbine

The ultimate limit of economy in operation, with any class of engine, is fixed by financial considerations, and the principle involved in determining the limit may be thus expressed -- :

That engine is most perfectly adapted to its place and purpose of which the type is such that no practicable substitution will permit the supply of the demanded power at lower total operative costs, including interest on first cost, sinking fund to provide for replacement at the end of its period of use, and annual operating expense; and that size of engine is on the whole best, variation from which in the direction of either increased or lessened size will increase that total expense of operation. In the latter case, the gain by reduction of size will be more than compensated by the loss due to its reduced efficiency. The best engine is that which will give largest returns on the capital invested, adding most effectively during its life to the dividends obtainable from the "plant" of which it forms a part.

The adjustment of the ratio of expansion of the steam to the requirements of maximum efficiency is the vital problem of the designing engineer and the purchaser of the engine. In the ideal case of the purely thermodynamic machine, this ratio is that of the initial to the backpressure, very nearly, and the terminal pressure on the expansion-line should coincide with the back-pressure. For maximum economy of fuel, this expansion ratio should be reduced in proportion, closely, to the loss by heat-wastes between boiler and piston. For maximum efficiency from the financial point of view, a still further reduction is required in proportion to the relation of the operating costs apart from those of steam-making to those of engine-operation proper. Thus, in the thermodynamic case, with initial and final pressures, respectively, 10 atmospheres and one, the ratio is reduced, often from about ten to seven or eight by initial condensation and minor wastes, and to six by adjustment to that value, departure from which, in either direction, would increase total costs of the horse-power hour.

With condensing engines, the ideal ratio might be 40 or 50, while the ratio for maximum duty would be not above 20, and the best ratio, from the point of view of the treasurer, might be not above 12 or 15. The accuracy with which the designing and constructing engineer determines the adjustment for maximum financial efficiency is a measure of his ability and skill and a gauge of his success in solving his problem. With each standard construction, experience usually enables the engineer to satisfactorily determine the proper solution of this problem.

The case of the steam-turbine exhibits here one of its essential peculiarities. The ratio of expansion is fixed by the conditions of its design, construction and operation and is necessarily the ratio of initial to back-pressure if properly constructed. The maximum efficiency of the turbine is obtained at its maximum power and it possesses the same inherent inflexibility as the hydraulic turbine, if of other than the "partial" class, in which latter case power is adjusted to load by varying the number of nozzles or supply-passages in action. It has the same possibilities of adaptation as has the hydraulic with, further, available recourse to intermittent supply, as with the Parsons turbine, a plan unavailable with the hydraulic machine, as an element of regulation. The steam-turbine, also, is not subject to internal condensation as all its elements, when in steady operation, maintain a constant temperature. Its economic theory is thus greatly simplified. Its financial theory simply dictates the construction of a light, rapidly moving vane and a minimum cost of application to its work, to operation and to maintenance, as a total. See ROTARY STEAM ENGINE.

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