Sulphur-Dioxide and the Binary Engine.*

BY R. H. THURSTON.

The "binary-vapor heat-engine," in its latest form, as illustrated by the machine employed at the Charlottenburg *Hoch Schule*, exhibits more clearly the advantages of the system than has any such apparatus previously reported upon, and the record produced under most satisfactory conditions is lower than was ever before known in the history of the economics of the heat-engines. Its consumption of steam, as a minimum, is reported as 8·36 pounds per horse-power-hour, 3·8 kilograms of moderately superheated steam, less than 9,500 B.T.U., or about 2,380 calories.† The power obtained was increased above one-third by the addition of this secondary system to the steam-engine and the economy was improved about 25 per cent. A gain of 20 per cent. was effected by the employment of superheated steam. The primary was a steam-engine of excellent construction and performance, having a "water-rate" of but about 11 pounds. These circumstances make it necessary to look upon the series-vapor engine much more seriously than has been customary. Such unquestionable economical advance must be carefully studied to ascertain whether the system can be made a commercially successful competitor of the common forms of heat-engine.

One of the first steps in such an examination of the case is the investigation of the scientific features of the system and the determination of the thermodynamic properties of the secondary fluid. As to the first of these questions there is no difficulty. The fact that the reduction of the lower limit of temperature of the heat-engine cycle is of more promise than an equal variation in the opposite direction at

* Presented to Section B, A.A.A.S., Washington Meeting, 1902.

† "Series-Vapor and Heat-Waste Engines," *Jour. Frank. Inst.*, R. H. T., October–December, 1902.

the upper limit was shown by Carnot, who asserted, seventy-five years ago, that

"*La chute du calorique produit plus de puissance motrice dans les degrès inférieurs que dans les degrès supérieurs.*" *

The second question, that regarding the relations of pressures, volumes and temperatures of the fluid, at the comparatively low temperatures of the exhaust-steam and the condenser, is settled by experience already had in the practical operation of the secondary engine employing the vapor. It gives high-working pressures at the temperatures at which it receives and discharges heat within the low and narrow range permitted its cycle when employed thus as a secondary. Steam at these lower ranges, while perfectly capable of providing 30 per cent. more power than is actually obtained from it in ordinary constructions, yields that power at so low an absolute pressure and at such a small mean pressure that it is quite unavailable in so cumbersome a machine as would be needed to develop it. It would require so large a proportion of its work to actuate the engine itself that its power-product would not be profitable. With the high mean pressures of the sulphur-dioxide vapor, the power developed is available in paying quantities.

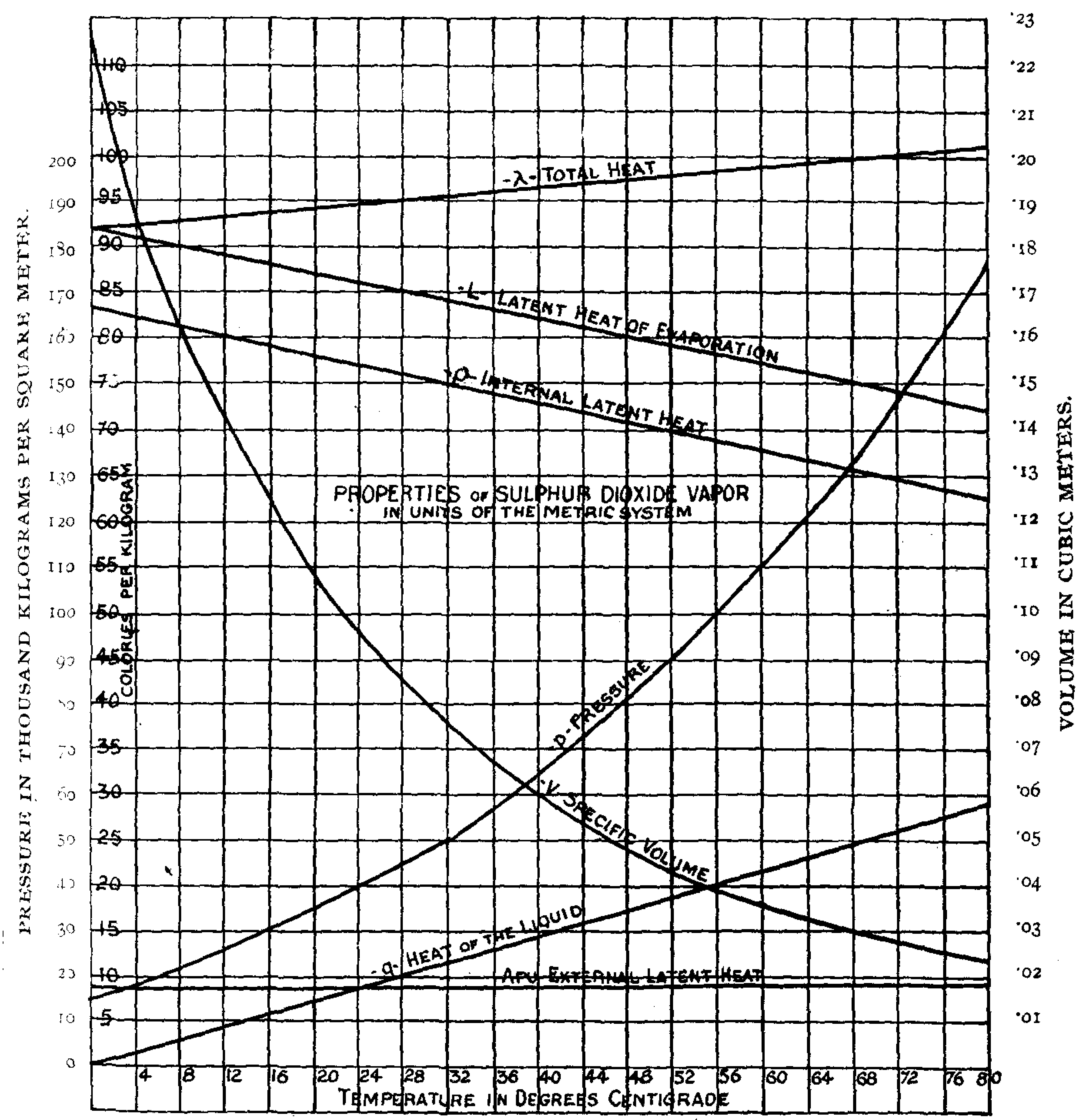
The question whether it will be practically possible to continuously employ this system as a commercial and profitable improvement upon the single-vapor engine must be settled by long experience under a great variety of conditions in regular business. The risks involved in handling the vapor, the wastes and costs of fluid, the disagreeables and the inconveniences, must all be more or less thoroughly evaded and extinguished. It is claimed that this has been accomplished. We shall know with certainty in due time.

The thermodynamic properties of the substance have not been fully investigated, and it will be interesting to ascertain just what advantage, if any, this substance has

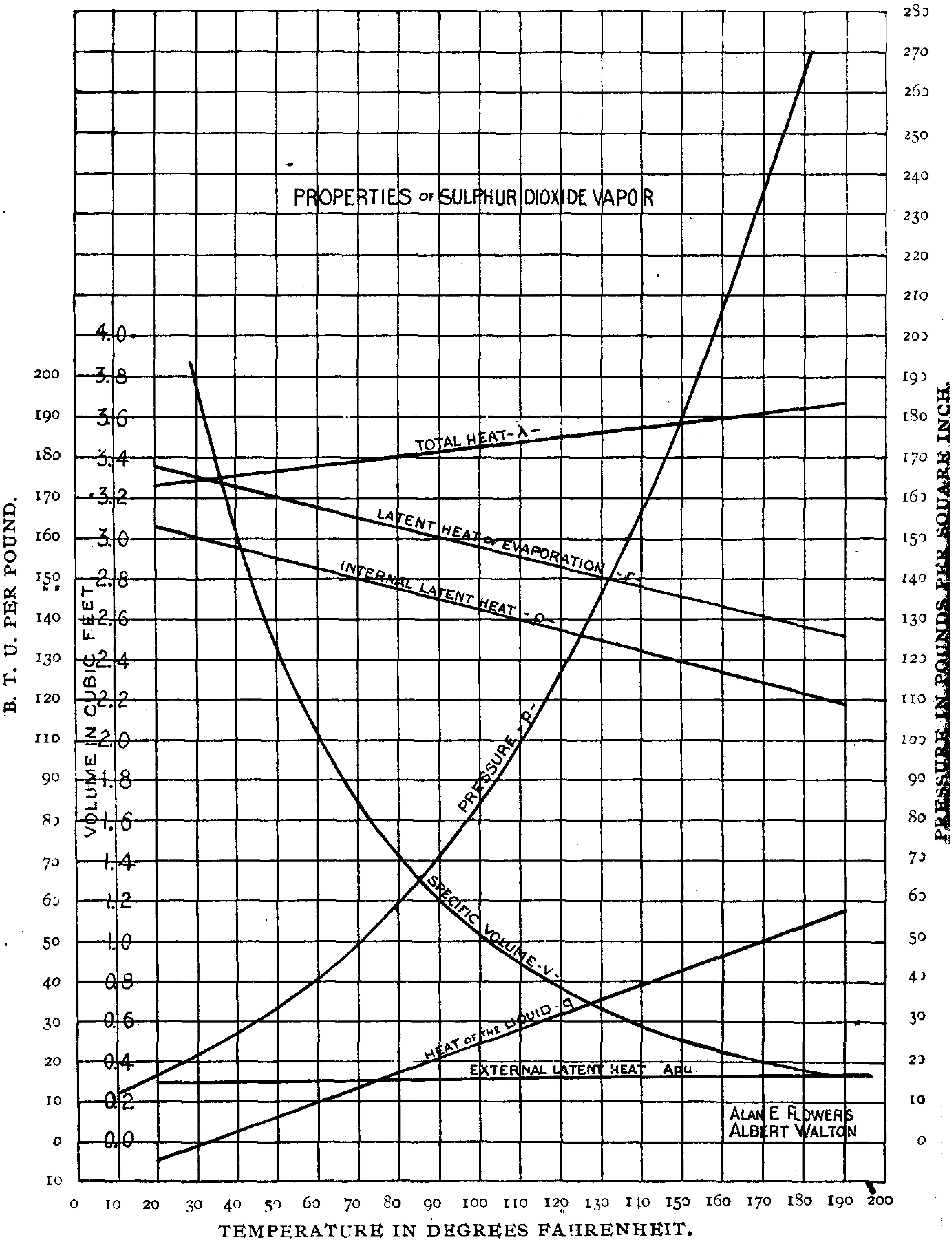
* "Réflexions sur la Puissance motrice du Feu." Paris: Gauthier-Villars, 1878.

"Reflections on the Motive Power of Heat and on Machines Fitted to Develop that Power." By N. L. S. Carnot. Thurston's translation. New York: J. Wiley & Sons, 1890.

over steam and other available working fluids. The adaptation of its pressure-volume relations to the prescribed temperature-range has been seen to be exceptionally perfect. The quantity of work which it may store in, and the suscepti-



bility of the substance to heat-exchange with, the metal of the working cylinder are yet to be determined; although the indications seem to be that, in common with the petroleum vapors and some other proposed secondary fluids, it has an advantage over steam in this respect. The oily fluids and



PROPERTIES OF SULPHUR DIOXIDE VAPOR
TOTAL HEAT - λ -
LATENT HEAT OF EVAPORATION - r -
INTERNAL LATENT HEAT - ρ -
PRESSURE - p -
SPECIFIC VOLUME - v -
HEAT OF THE LIQUID - q
EXTERNAL LATENT HEAT Apu
ALAN E. FLOWERS
ALBERT WALTON
B. T. U. PER POUND.
VOLUME IN CUBIC FEET
PRESSURE IN POUNDS PER SQUARE INCH.
TEMPERATURE IN DEGREES FAHRENHEIT.

the gases do not readily transfer heat by conduction; while steam, on the contrary, possesses a remarkable power of discharge of its heat into a cooler metal and of regaining it when the temperature relations are reversed.

A study of the ideal cycle for this case will give interesting facts and will permit later comparison of the behavior of the real engine with its ideal. In this comparison, the main differences may be expected to prove to be due to the differences in readiness of heat-exchange, the ideal case being entirely free from this sort of waste.

A preliminary study of the tabulated physical properties of the substance should preface this investigation. It will be found that the published tables are usually incomplete and sometimes contain errors which must be carefully checked out. The tables are usually very narrow in range and very limited in number of points of observation. The original authority is Regnault, and it is necessary to go back to his paper in the "Memoirs of the French Academy," Vol. XXVI, for the original experimental data. Later writers have proposed various formulas connecting pressures and temperatures, and, among these, perhaps the best is that of Ledoux.* The work of rectification of data and of smoothing up the tables was undertaken, at the suggestion of the writer, by Messrs. A. E. Flowers and Albert Walton. The tables obtained, reduced to both metric and British measures, are herewith presented. The results of computation of the limited number of points determined were laid down, and the smooth curve thus obtained permitted the detection of errors of computation and a complete rectification of the tables. The originals of the curves for both British and metric measures are preserved in the collections of Sibley College.†

All the values are based on Regnault's experiments; but the formulas used were those proposed by later writers. The quantities were computed at temperatures between 0° C. and 80° C. (32° F. and 176° F.). The values for the

---

* "Annales des Mines," 1878.

† *Sibley Journal of Mechanical Engineering*, June, 1902.

higher temperatures are presumably not absolutely correct, as they were computed by means of formulas based on experiments at lower temperature ranges; but they are the best that could be obtained.

FORMULAS AND METHODS OF COMPUTATION.

Pressure.—Ledoux gives, in the "Annales des Mines," 1878, the following formula for the boiling pressure at different temperatures:

$$p = a\,\alpha^{\frac{t}{1+mt}}$$

in which

p = Pressure in kilograms per square meter.
t = Temperature in degrees centigrade.
a = 15,840, a constant; log a = 4·199755.
α = 1·04154, a constant; log α = ·017673.
m = ·0043129, a constant; log α = 8·247318 — 10.

In the original article by Ledoux the value for α is given as 1·04135. The above value for α was computed from the value given by Regnault for the pressure at 35° C.

The following formulas are from Peabody's tables as adapted from Ledoux:

Heat of the liquid, $q = \cdot 36333\, t + \cdot 00004\, t^2$.

Total heat, $\lambda = 91\cdot 396 + 0\cdot 12723\, t - \cdot 000131\, t^2$.

Latent heat of evaporation, $L = 91\cdot 396 - \cdot 2361\, t - \cdot 000135\, t^2$.

External latent heat, $Apu = 8\cdot 243 + \cdot 196\, t - \cdot 000116\, t^2$.

Internal latent heat, $\rho = L - Apu$.

Specific volume,

$$v = \frac{BT - Cp^n}{p};$$

where

$$B = 13\cdot 882$$
$$C = 3\cdot 8455$$
$$n = 0\cdot 4487$$

By means of these formulas the quantities were computed for the desired range. These were then converted from the metric to the British system of units, and, for ease in interpolation, plotted on a large sheet of co-ordinate paper, using for common abscissas degrees of temperature.

SYMBOLS EMPLOYED IN TABLE I (METRIC UNITS).

t = Temperature in degrees centigrade.
p = Pressure in kilograms per square meter at which evaporation takes place.
q = Heat of liquid in calories per kilogram.
λ = Total heat of evaporation above 0° C. in calories per kilogram.
L = Latent heat of evaporation in calories per kilogram.
ρ = Internal latent heat in calories per kilogram.
Apu = External latent heat of evaporation in calories per kilogram.
S = Specific volume of the saturated vapor in cubic meters per kilogram.

SYMBOLS EMPLOYED IN TABLE II (BRITISH UNITS).

t = Temperature in degrees Fahrenheit.
p = Pressure of dry and saturated vapor boiling at the given temperature.
q = Heat of the liquid in B.T.U. per pound.
λ = Total heat of evaporation in B.T.U. per pound.
L = Latent heat of evaporation in B.T.U. per pound.
ρ = Internal latent heat of evaporation in B.T.U. per pound.
S = Specific volume of vapor in cubic feet per pound.

SATURATED VAPOR OF SULPHUR-DIOXIDE.

TABLE I. METRIC UNITS.

t	p	q	λ	L	ρ	Apu	S
0	15840	0	91·396	91·396	83·153	8·243	·22583
5	19331·2	1·817	92·027	90·212	81·870	8·342	·18337
10	23397·9	3·673	92·655	89·022	80·595	8·427	·15345
15	28102·6	5·46	93·27	87·82	79·31	8·51	·1292
20	33508·5	7·28	93·89	86·62	78·03	8·59	·1096
25	39681·2	9·11	94·49	85·41	76·75	8·66	·09348
30	46688·8	10·93	95·09	84·19	75·46	8·73	·08025
35	54601·0	12·77	95·69	82·97	74·19	8·78	·06929
40	63485·4	14·60	96·27	81·73	72·89	8·84	·06015
45	73416·3	16·43	96·85	80·49	71·60	8·89	·05248
50	84462·7	18·27	97·43	79·25	70·32	8·93	·046007
55	96698·9	20·10	98·00	78·00	69·03	8·97	·04052
60	110194·0	21·94	98·56	76·74	67·74	9·00	·03584
65	125024·0	23·79	98·81	75·48	66·45	9·03	·031835
70	141222·0	25·63	99·66	74·21	65·16	9·05	·028387
75	158961·0	27·47	100·20	72·93	63·87	9·06	·025407
80	178210·0	29·32	100·74	71·64	62·57	9·07	·022820

TABLE II. BRITISH UNITS.

t	p	q	λ	L	ρ	Apu	S
32	22·53	0	164·51	164·51	149·67	14·84	3·6173
41	27·49	3·27	165·65	162·38	147·36	15·02	2·9380
50	33·28	6·55	166·78	160·24	145·07	15·17	2·457
59	39·97	9·83	167·88	158·08	142·75	15·32	2·061
68	47·66	13·10	169·00	155·91	140·45	15·46	1·756
77	56·44	16·39	170·08	153·74	138·15	15·59	1·498
86	66·41	19·67	171·16	151·54	135·83	15·71	1·286
95	77·66	22·98	172·24	149·35	133·54	15·80	1·120
104	90·30	26·28	173·29	147·11	131·20	15·91	·964
113	104·42	29·57	174·33	144·88	128·88	16·00	·841
122	120·13	32·89	175·37	142·65	126·58	16·07	·737
131	137·53	36·18	176·40	140·40	124·25	16·15	·649
140	156·73	39·49	177·40	138·13	121·93	16·20	·574
149	177·82	42·82	178·40	135·86	119·61	16·25	·510
158	200·86	46·13	179·39	133·58	117·29	16·29	·4547
167	226·09	49·45	180·36	131·27	114·97	16·31	·4070
176	253·47	52·78	181·33	128·95	112·62	16·33	·3656

Employing these data, as required, in the comparison of the work of the Berlin secondary engine, from the published accounts of the engine-trials of the machines of which it constitutes an element, we may secure some interesting results. The process adopted by the computers is that usually followed by the writer, adopting the general method of Rankine, with the supplementing and modernization of that system by the introduction, in the real case, of those wastes which do not appear in the purely thermodynamic case. In the present example the question of most interest is that of quantity of extra-thermodynamic waste where the volatile secondary fluid is employed. The data for the real case have been published and are accessible and undoubtedly are entirely accurate.*

The heat reaching the secondary element is that which enters the primary, less the loss, *en route*, by conduction and radiation. The cylinder-condensation waste, it is to be remembered, is not lost as a supply to the succeeding cylinder in any case. All that is absorbed by the metal at entrance

* Berlin Royal Technical High School; Report No. 11, 1899. In English, German and French. Also "Series Vapor and Heat-Waste Engines" R. H. T., *Jour. Frank. Inst.*, October–December, 1902.

of the steam is rejected with the exhaust. It is only the external waste by conduction and radiation and the transformed energy which leaves the system absolutely. Even the friction of the piston in the cylinder reproduces heat, by reconversion of mechanical work into heat, for use by the succeeding element. The heat reaching the larger cylinders of the primary and of the secondary is thus very nearly the full amount entering the high-pressure cylinder of the primary element of the binary engine, less only the equivalent of work performed.

In the tabulated results of Professor Josse's experiments are given the temperatures and pressures of entering and exhaust steam and of entering and exhaust sulphur-dioxide. The limits for the ideal cycles computed were taken as the sulphur-dioxide pressures given for the tests recorded as Nos. 4, 7, 8 and 12.* The initial pressure, p_1, is taken as the absolute pressure at the vaporizer, while the final pressure, p_2, is the absolute pressure of the condenser. In this, the atmospheric pressure is assumed to be the average value of 14·5 pounds per square inch. From these pressures the corresponding values required for computation were found on the curves, as tabulated on the accompanying data sheet.

The heat actually supplied to the SO_2 engine was taken as the total available heat of the superheated entering steam, less the heat-equivalent of the indicated work in the steam-engine, and with a certain allowance for external radiation and conduction losses. The allowance for these losses was about 3 per cent. of the total amount of heat entering the steam-engine. The loss was assumed to be slightly greater for the one case where the steam was nearly saturated, 80,000 B.T.U. per hour being allowed, and 70,000 B.T.U. per hour in the other cases.

The amount of the thermal waste was taken as the difference between the heat-input so calculated and the heat required for an *ideal* SO_2 engine of equal power working through the same range. The amount of this waste, divided by the range of temperature worked through, and by the

* *Jour. Frank. Inst.*, December, 1902.

area of the internal surface of the SO_2 cylinder, gave the heat-waste in B.T.U. per square foot per degree difference of temperature per hour. This quantity was divided by 60 to reduce it to the heat-waste per minute. The figure thus found for the heat-waste is about that observed for simple condensing steam-engines.

DETERMINATION OF AMOUNT OF HEAT ENTERING SO_2 ENGINE.*

	I.	II.	III.	IV.
Temperature of boiler steam	189·5	302·0	330·0	301·0
Temperature Fahrenheit	373·1	575·6	626·0	573·8
Pressure, lbs per sq. in. gage	156·5	156·5	156·5	158·0
Pressure, lbs., absolute	171·0	171·0	171·0	172·5
Corresponding temperature	368·6	368·6	368·6	369·3
Total heat above 32° of dry saturated steam B.T.U. per lb.	1194·4	1194·4	1194·4	1194·6
Superheat, degrees	4·5	207	257·4	204·5
B.T.U. per lb. due to superheat, 0·4805 x D	2·16	99·5	123·7	98·3
Total heat of steam above 32° in B.T.U. per lb.	1196·6	1293·9	1318·1	1292·9
Per cent. of vacuum	68·2	79·5	75·2	68·5
Absolute pressure of vacuum	4·61	2·975	3·598	4·57
Heat of liquid of exhaust	127·0	109·6	116·6	126·6
Available heat in steam in B.T.U. per pound	1069·7	1184·6	1201·5	1166·3
Total weight of steam per hour	2562	1980	1197	2142
Available heat in steam in B.T.U. per hour	2740571	2345508	1438195	2383197
Horse-power of steam-engine	156·3	145·3	82·4	163·2
B.T.U. equivalent of I.H.P.	397783	369788	209708	415344
Assumed loss by radiation and conduction	80000	70000	70000	70000
B.T.U. per hour available for SO_2 engine	2262788	1905720	1158487	2012871
Horse-power of SO_2 engine	66	50·1	30·6	54·7
Heat required for ideal engine of same range and H.P.	1375440	1189073	635195	1048052
Heat-waste in B.T.U. per hour	887348	716647	523292	964819
Temperature range	82·35	69·40	81·70	90·83
Internal area of SO_2 cylinder in sq. ft.	5·692			
Heat-waste in B.T.U. per degree per square foot per hour	1893	1814	1125	1644
Heat-waste in B.T.U. per degree per square foot per minute	31·55	30·23	18·75	27·39

*See Manual of the Steam-Engine, Thurston. Vol. I, p. 995, *et seq.*

SYMBOLS, TABLE III.*

p_1 = Absolute initial pressure = gage pressure in vaporizer + 14·5 pounds per square inch, atmospheric pressure.

T_1 = Absolute temperature in Fahrenheit degrees = 461° + temperature of ebullition, from curve.

v_1 = Initial volume of SO_2 vapor, from curve.

p_2 = Absolute final pressure in SO_2 condenser, 14·5 pounds per square inch, the assumed pressure of the atmosphere.

T_2 = Absolute final temperature in Fahrenheit degrees, temperature of ebullition corresponding to p_2, from curve.

v_2 = The final volume of SO_2 vapor, from curve.

r = Ratio of expansion = $V_2 + V_1$.

λ = Total heat of entering SO_2 vapor, from curve.

q_2 = Heat of the liquid of exhaust, from curve.

L = Latent heat of evaporation, from curve.

H_1 = Energy per pound in foot-pounds of entering SO_2 = $J(\lambda - q_2)$.

H' = Energy per pound in foot-pounds of the latent heat of evaporation = JL.

U = Useful energy per pound of SO_2 vapor in foot-pounds

$$= Jc'\left(T_1 - T_2\left(1 + \log_e \frac{T_1}{T_2}\right)\right) + \frac{T_1 - T_2}{T_1} H'.$$

E = Efficiency

$$= \frac{U}{H}.$$

$M.E.P.'$ = Mean effective pressure in pounds per square foot

$$= \frac{U}{v_2}.$$

$M.E.P.''$ = Mean effective pressure in pounds per square inch

$$= \frac{M.E.P.'}{144}.$$

---

* *Ibidem.*

A = B.T.U. per I.H.P. hour

$$= \frac{2545}{E}.$$

B = Pounds of SO_2 per I.H.P. hour for efficiency unity

$$= \frac{1980000}{H_1}$$

C = Pounds of SO_2 per I.H.P. hour for actual efficiency

$$= \frac{B}{E}.$$

D = Piston displacement per I.H.P. hour = Cv_2.

D' = Piston displacement per I.H.P.

$$= \frac{D}{60}.$$

F = Pounds of exhaust steam per I.H.P. hour = A divided by the latent heat of the exhaust steam.

J = Mechanical equivalent of heat = 778 foot-pounds.

c' = Specific heat of SO_2 liquid found from curve between temperature limits of 50° and 158° F. = 0·3665.

The formula for U, as given, is based on the assumption that the expansion is complete, and that the final pressure is equal to the back pressure.

SULPHUR-DIOXIDE CYCLES.

	I.	II.	III.	IV.
T_1	616·5	600·95	610·6	621·0
p_1	194·5	156·7	179·4	206·5
v_1	0·468	0·574	0·506	0·443
T_2	534·15	531·55	528·9	530·17
p_2	52·5	50·0	47·6	48·7
v_2	1·602	1·678	1·760	1·720
r	3·425	3·923	3·478	3·882
λ_1	179·05	177·35	178·40	179·50
q_2	15·0	14·05	13·10	13·6
L	134·2	138·25	135·7	133·1
H_1	127630	127047	128603	129070
H'	104400	107558	105574	103552
U	15587	13623	15765	17144
E	·12212	·10723	·12260	·13283

M.E.P.'	9729·7	8118·7	8957·4	9967·4
M.E.P.''	67·56	56·37	62·20	69·21
A	20840	23734	20758	19160
B	15·514	15·58	15·40	15·34
C	127·04	145·29	125·60	115·49
D	205·82	243·80	221·06	198·64
D'	3·43	4·063	3·68	3·31
F	20·182	23·367	20·554	19·061

The expenditure of heat in the secondary cycle, A, thus averages, for the ideal case, about 20,000 B.T.U. per I.H.P. hour, not a remarkably low figure; but on the other hand, it costs nothing, as it is supplied by the waste of the primary element of the combination. The quantity of SO_2 per I.H.P. hour for unity efficiency, B, under the conditions of its employment in this case, is a trifle above 600 pounds; but this amount is unimportant, commercially, as this is a circulatory system, and once the charge is received into the system, it costs nothing except for renewal or leakage. The quantity demanded for the actual efficiency, C, is about 130 pounds and the same remark here applies. The piston displacement per I.H.P. hour, D, is about 220 cubic feet, and this will vary with the mean effective pressure on the piston. The same figure, reduced to expenditure per minute, becomes about 3·66. The weight of steam entering the secondary element, per I.H.P. hour, F, averages a little more than 20 pounds.

Comparing these figures with those of the trials, as observed and reported as the actual consumption of heat and steam in the secondary engine, it is found that about one-half of the supply to that element is wasted by extra-thermodynamic methods of rejection. How much of this is leakage and how much is thermal waste cannot be determined from the data. It does not appear, however, from this examination of the case that the wastes are less than in the steam-engine in similar cycles. It is, however, sufficiently evident that the main source of the gain observed, when the secondary element with its volatile working fluid is introduced, is to be found in the fact that the result is the securing of high absolute pressures and of large mean effective pressures, with relatively small variation of volumes, at a part of the thermal range at which steam does not give us pressures of sufficient magnitude to permit the maintenance of satisfactory mechanical efficiency of the engine or to produce commercially satisfactory sizes and weights of the motor.*

MINUTE MECHANISM.

Modern Machinery contains some interesting facts about the minuteness of some of the screws made in an American watch factory. It takes nearly 130,000 of a certain kind to weigh a pound. Under a microscope, they appear in their true character—perfectly finished bolts. The pivot of the balance wheel is only $\frac{1}{200}$ of an inch in diameter, and the gage with which pivots are classified measures to the $\frac{1}{10000}$ part of an inch. Each jewel hole in which a pivot fits is about $\frac{1}{5000}$ of an inch larger than the pivot to permit sufficient play. The finest screw for a small-sized watch has a thread of 260 to the inch, and weighs $\frac{1}{150000}$ of a pound. Jewel slabs of sapphire, ruby or garnet are first sawed into slabs $\frac{1}{50}$ of an inch thick and are shellacked to plates so that they may be surfaced. Then the individual jewels are sawed or broken off, drilled through the center, and a depression made in the convex side for an oil cup. A pallet jewel weighs $\frac{1}{150000}$ of a pound; a roller jewel a little more than $\frac{1}{250000}$. The largest round hairspring stud is $\frac{4}{100}$ of an inch in diameter and about $\frac{9}{100}$ of an inch in length.

ALUMINUM ALLOYS.

Aluminum World is authority for the statement that an alloy consisting of 18·87 per cent. of aluminum and 81·13 per cent. of antimony is a marked exception to the general rule that alloys are more fusible than the least fusible metal contained. Aluminum and antimony melt at nearly the same point, which is in the neighborhood of 1,160° F.; this alloy does not melt until a temperature of 1,976° F. is reached. Most alloys are denser than their constitutents; this alloy is less dense. Quantitatively, 7·07 cubic inches of aluminum, alloyed with 12·07 of antimony, produces 23·71 cubic inches of alloy, thus showing an increase in volume of 4·55 cubic inches, or 24 per cent.

The *Iron Age* gives us the following item:

A French engineer is alleged to have discovered alloys for aluminum which impart to this metal most extraordinary qualities. By varying the amount of his alloy from 1 part in 12 to 1 part in 240 he obtains compounds varying in tensile strength from 29,000 to 58,000 pounds per square inch. These are so different in characteristics that they may be chased, soldered, brazed, forged, rolled into plates and leaves, or drawn into wire, all depending on the amount of the alloy. It can be made soft, like pure aluminum, or stiff and rigid like steel, and possessed of nearly the same strength, on one-third the weight.

* For details of methods of treatment and of computation, see Manual of the Steam-Engine, Vol. I, §§ 137, 149, 155, and notes, pp. 995–1004. R. H. T.