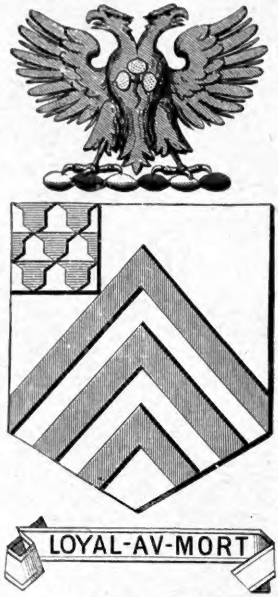

LOYAL-AV-MORT

PRACTICAL LAWS AND DATA

ON THE

CONDENSATION OF STEAM

IN

COVERED AND BARE PIPES

TO WHICH IS ADDED

A

TRANSLATION OF PÉCLET'S "THEORY AND EXPERIMENTS ON THE TRANSMISSION OF HEAT THROUGH INSULATING MATERIALS."

BY

CHARLES P. PAULDING, M.E.

PREFACE

The main object of this book is to bring to the attention of engineers an accurate and rational method of estimating the loss of heat from steam pipes and boilers covered with any of the well known non-conducting materials now on the market. This method worked out long ago by Péclet seems to have been generally overooked in this country, perhaps because no translation of Péclet's work existed.

The principles involved are so general in their application that it is believed that the fuller explanation of them, to be found in the appended translation, together with the experiments on which they are based, will be of some general interest. This matter will be of use to heating engineers in cases which are not taken care of by their usual rules, and of great value as an aid to the cultivation of that broad view of a problem so necessary to practical success. To the refrigerating engineer and designer of cold storage warehouses these principles are indispensable.

CONTENTS

THE LOSS OF HEAT FROM COVERED STEAM PIPES

In the last few years a number of elaborate and careful tests have been made on various coverings for steam pipes. These tests have been made for the intending purchaser with the point of view of ascertaining the most efficient of the pipe coverings regularly on the market. They have no doubt served this purpose admirably, but it has occurred to the writer that they might also be made to serve the purpose of guiding the manufacturer as to the true values of the materials used in the coverings, and to aid the engineer in computing the losses from pipes already covered, or the saving to be effected by increasing the covering or using a more efficient material.

The true value of the different materials used in the tests has been notably obscured by the different thicknesses, and no law governing the general subject has been even hinted at in the published reports of the tests.

As long ago as 1850 the great French physicist Péclet (Péclet-Traité de la Chaleur—Paris, 1860) investigated with wonderful skill and patience the laws of the emission of heat from a surface maintained at constant temperature, and the laws of conduction of heat through materials of low conductivity. His experiments, though on a small scale and strictly laboratory ones, were so cleverly planned and skillfully executed that the laws empirically deduced from them could hardly fail to be correct.

The loss of heat from covered pipes is only one of their many practical applications.

When an iron steam pipe, of customary thickness, covered with material of low conductivity, is filled with steam at rest or moving with ordinary velocity, the amount of heat escaping through the covering is so small compared with what the metal of the pipe could transmit, that the outer surface of the pipe attains the same temperature as the steam within it.

Leaving the surface of the pipe, the heat is transmitted through the cylindrical covering by virtue of the conductivity of that covering, and when it has reached the surface it is dissipated to the surrounding objects and the surrounding air by radiation and contact of air.

We have then two phenomena to deal with, the conduction of the heat through the covering and its escape from the surface of the same.

For the latter Péclet gives the following laws: "The quantity of heat emitted by a surface at constant temperature depends on the radiation and the contact of air."

"The quantity of heat emitted by radiation, per square foot of surface, per hour, is independent of the form and size of the body, provided that it has no reëntrant portions. It depends solely on the nature of the surface of the body, on the excess of its temperature over that of the objects to which radiation takes place, and on the absolute value of the temperature of these objects."

For paper and cloth, Péclet found that color had no influence on the radiation.

The following table gives the values found by him for radiation from different surfaces:

VALUES OF K.

B. T. U. PER HOUR PER SQUARE FOOT PER ONE DEGREE.

Tin plate	.086	Cast iron, new	.650
Polished sheet iron	.092	" " rusty	.688
Ordinary " "	.567	Sheet iron, rusty	.688
Oil paint " "	.759	Paper	.772
Plaster or wood	.737	Calico or canvas	.747

The coefficients by which these numbers must be multiplied for any excess of temperature are given in figure 2. The temperature of the objects radiated to would generally be the same as that of the surrounding air. It is taken so in all calculations throughout this article.

The coefficients by which the numbers in the table must be multiplied for any given temperature of the objects radiated to are given by figure 3.

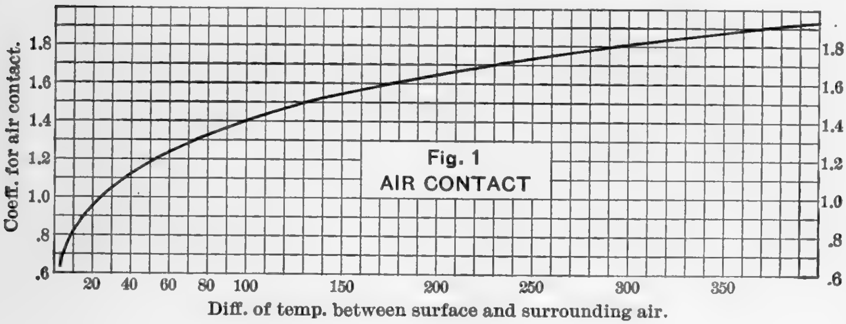
For an example take a covering on a hot steam pipe. The surface of these coverings is invariably formed by canvas.

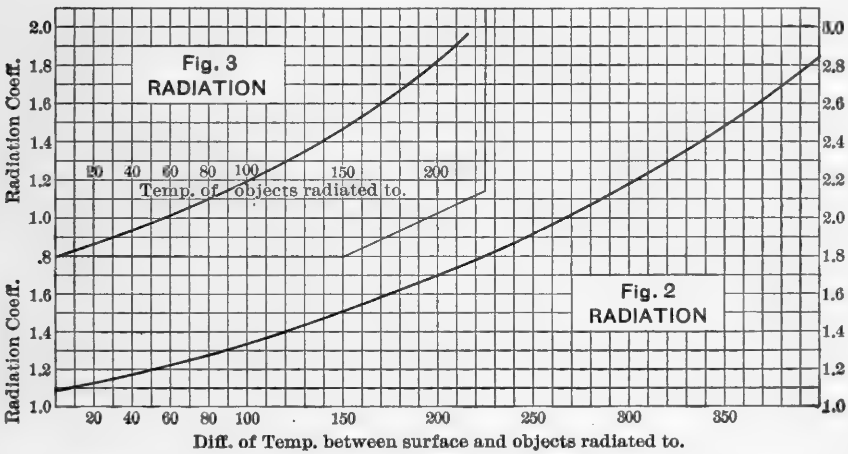
Consider a square foot and let its temperature be 125° F., and that of the surrounding objects and air 85° F., then the excess of temperature will be 40 degrees.

The loss per square foot per hour due to radiation will be,

$$R \times 40 = (.747 \times 1.17 \times 1.12)(40) = 39.2.$$

"The loss of heat arising from air contact is independent of





the nature of the surface of the body, and of the absolute temperature of the surrounding air; it depends solely on the excess of temperature of the surface of the body over the temperature of the surrounding air, and on the form and dimensions of the body."

Figure 4, for horizontal cylinders, and Figure 5 for vertical

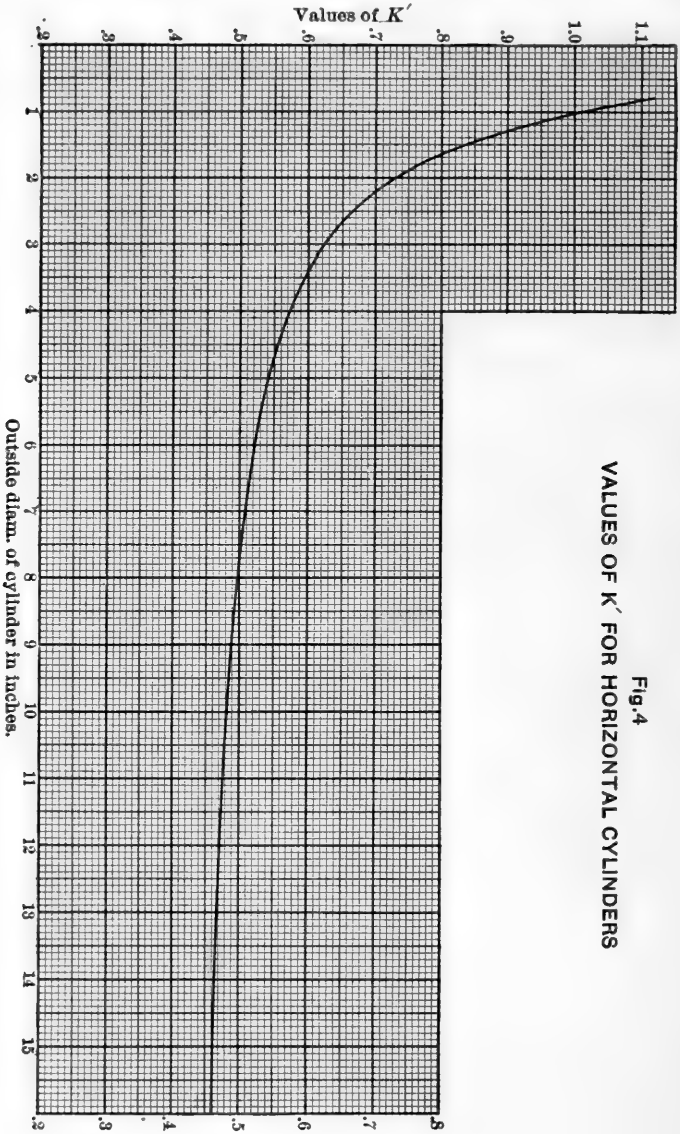
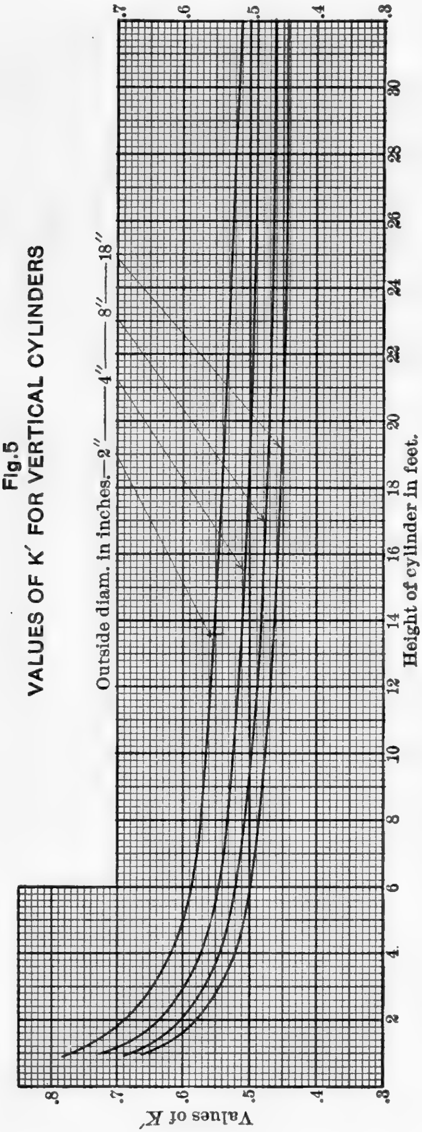


Fig.4
VALUES OF K′ FOR HORIZONTAL CYLINDERS

Fig.5

VALUES OF K′ FOR VERTICAL CYLINDERS



ones, give the values of the heat loss by air contact per square foot per hour per one degree.

Figure 1 gives the coefficients by which these values are to be multiplied for any given difference of temperature between the surface of the body and the air.

Assume that the outside diameter of the covering in the example used above for radiation loss is six inches, and that the pipe is horizontal. Then under the same conditions, a difference of temperature of 40 degrees, the air contact loss is

$$A \times 40 = (.52 \times 1.13)(40) = 23.5.$$

The combined loss for this square foot of surface of covering under the conditions given is therefore,

$$39.2 + 23.5 = 62.7 \text{ B. T. U. per hour.}$$

In a test the temperature of the air should be measured before the air reaches the heated covering and the thermometer should be protected from radiation from the covering.

We may now consider the conduction of the heat through the covering.

The law for a flat plate of insulating material is very simple; the quantity of heat transmitted per square foot per hour varies directly as the conductivity of the material, inversely as its thickness, and directly as the difference of temperature between the two surfaces of the plate.

Note that it is the temperatures of the surfaces of the plate, not of the air in contact with the surfaces.

The formula for a flat plate is then,

$$M = \frac{C(t - t')}{E}$$

where t and t' are the surface temperatures,

C the coefficient of conductivity,

E the thickness in inches, and

M the heat transmitted in B. T. U. per square foot per hour.

For a cylinder, the principle is the same but the expression changes. Consider a section one foot long.

Let R and R' be the inside and outside radii, in feet, of the cylinder of insulating material,

t and t' the respective surface temperatures, and

θ the temperature of the surrounding air.

Consider an infinitely thin annular element of the covering at radius r, its thickness is dr, its area, $2\pi r$, its conductivity for one foot thickness is C' and the difference between the temperatures of its inner and outer surfaces is dt. Then treating it as a flat plate we have
$$M' = -\frac{2\pi r\ C'\ dt}{dr}$$

Integrating we have $M' = \dfrac{2\pi C'\ (t-t')}{N}$ . . . . . . (1)

where $N = 2.3\ (\log R' - \log R)$.

Now we have already shown that for a square foot of surface $M = (A+R)\ (t'-\theta)$ and remembering that $M' = 2\pi R'\ M$ and calling $A+R=Q$ we have

$$M' = 2\pi R'\ Q\ (t'-\theta) \quad . \ . \ . \ . \ . \ . \ . \ . \quad (2)$$

The amount of heat passing through the covering must equal that escaping from the surface, so setting (1) equal to (2) we get

$$M' = \frac{2\pi R'\ Q\ (t-\theta)}{1 + \dfrac{Q\ R'\ N}{C'}} \quad . \ . \ . \ . \ . \ . \ . \quad (4)$$

It is more convenient to use C the coefficient of conductivity for one inch thickness instead of C' the coefficient for one foot. Since $C = 12\ C'$ we get

$$M' = \frac{2\pi R'\ Q\ (t-\theta)}{1 + \left(\dfrac{Q\ R'\ N}{C}\right)12} \quad . \ . \ . \ . \ . \ . \ . \quad (4)$$

It is really more convenient to keep R' in feet. In working up the value of $N = 2.3\ (\log R - \log R')$ from a table of logarithms we can, of course, take R and R' in inches if we wish.

For an example take a 10-inch pipe, covered with a thickness of $1\frac{3}{16}$ inches of Keasbey's Magnesia; steam temperature 365.2° F.; air temp. 66° F.; $C = .45$.

The difference between the logarithms of the inner and outer radii is $.087 \times 2.3 = .2 = N$.

We cannot yet compute the exact value of Q because we do not know the temperature of the surface of the covering, but we will assume it to be 1.7.

Then $M' = \dfrac{3.44 \times 1.7\ (365.2 - 66)}{1 + \left(\dfrac{1.7 \times .548 \times .2}{.45}\right)12} = 293.$

TABLE FOR USE WITH THE FORMULAS OF PAGE 7

NOMINAL PIPE SIZE	THICKNESS OF COVERING IN INCHES	RADIUS IN FEET R'	SQUARE FEET PER FOOT RUN $2\pi R'$	N	$12R'N$	NOMINAL PIPE SIZE	THICKNESS OF COVERING IN INCHES	RADIUS IN FEET R'	SQUARE FEET PER FOOT RUN $2\pi R'$	N	$12R'N$
1″	0	.055	.356	......	......	1½″	0	.078	.491	......	......
	½	.097	.609	.567	.660		½	.121	.759	.458	.665
	⅝	.108	.676	.669	.864		⅝	.132	.828	.521	.823
	¾	.118	.738	.758	1.069		¾	.142	.890	.594	1.009
	⅞	.128	.806	.847	1.300		⅞	.153	.959	.668	1.220
	1	.138	.870	.921	1.530		1	.163	1.022	.731	1.425
	1⅛	.149	.937	.997	1.785		1⅛	.173	1.090	.796	1.655
	1¼	.159	1.000	1.062	2.028		1¼	.183	1.152	.852	1.875
	1⅜	.170	1.068	1.128	2.302		1⅜	.194	1.220	.910	2.120
	1½	.180	1.130	1.185	2.560		1½	.204	1.283	.959	2.350
2″	0	.099	.62	......	......	2½″	0	.120	.75	......	......
	½	.141	.89	.351	.593		½	.162	1.02	.298	.579
	⅝	.152	.95	.426	.775		⅝	.172	1.08	.358	.738
	¾	.162	1.02	.489	.950		¾	.183	1.15	.419	.918
	⅞	.173	1.08	.554	1.145		⅞	.194	1.22	.477	1.106
	1	.183	1.15	.610	1.335		1	.204	1.28	.528	1.290
	1⅛	.193	1.22	.668	1.548		1⅛	.213	1.34	.574	1.469
	1¼	.204	1.28	.722	1.767		1¼	.223	1.40	.620	1.651
	1⅜	.214	1.35	.770	1.976		1⅜	.234	1.47	.667	1.872
	1½	.224	1.41	.814	2.190		1½	.245	1.54	.713	2.093
3″	0	.146	.92	......	......	4″	0	.188	1.18	......	......
	½	.188	1.18	.251	.565		½	.229	1.44	.201	.553
	⅝	.199	1.25	.308	.734		⅝	.240	1.51	.247	.710
	¾	.208	1.31	.356	.890		¾	.250	1.57	.288	.864
	⅞	.219	1.38	.407	1.070		⅞	.260	1.64	.332	1.038
	1	.229	1.44	.451	1.240		1	.271	1.70	.368	1.196
	1⅛	.240	1.51	.497	1.430		1⅛	.282	1.77	.407	1.374
	1¼	.250	1.57	.538	1.614		1¼	.292	1.83	.442	1.545
	1⅜	.261	1.64	.581	1.815		1⅜	.303	1.90	.478	1.736
	1½	.271	1.70	.618	2.010		1½	.313	1.96	.511	1.915
5″	0	.232	1.46	......	......	6″	0	.276	1.73	......	......
	½	.273	1.72	.165	.541		½	.318	2.00	.140	.534
	⅝	.284	1.79	.203	.692		⅝	.328	2.06	.173	.682
	¾	.294	1.85	.238	.840		¾	.338	2.13	.203	.824
	⅞	.305	1.92	.275	1.006		⅞	.349	2.19	.235	.984
	1	.315	1.98	.307	1.160		1	.359	2.26	.263	1.133
	1⅛	.325	2.04	.338	1.318		1⅛	.370	2.32	.293	1.300
	1¼	.336	2.11	.372	1.500		1¼	.380	2.39	.320	1.460
	1⅜	.347	2.18	.402	1.671		1⅜	.391	2.45	.348	1.630
	1½	.357	2.24	.432	1.847		1½	.401	2.52	.373	1.795
8″	0	.359	2.26	......	......	10″	0	.449	2.82	......	......
	½	.401	2.52	.110	.529		½	.490	3.08	.088	.518
	⅝	.412	2.59	.137	.678		⅝	.501	3.15	.110	.662
	¾	.422	2.65	.161	.815		¾	.511	3.21	.130	.796
	⅞	.433	2.72	.186	.965		⅞	.522	3.28	.150	.940
	1	.443	2.78	.209	1.110		1	.532	3.34	.170	1.085
	1⅛	.453	2.84	.232	1.260		1⅛	.542	3.41	.190	1.236
	1¼	.463	2.91	.255	1.426		1¼	.552	3.47	.209	1.385
	1⅜	.474	2.98	.278	1.583		1⅜	.564	3.54	.228	1.541
	1½	.484	3.04	.299	1.738		1½	.574	3.61	.247	1.700

Then, by (2)

$$293 = 3.44 \times 1.7\ (t' - 66),$$
$$t' = 116. \quad \text{Then } 116 - 66 = 50.$$

We may now find Q for $50°$ difference of temp.

$$R = .75 \times 1.2 \times 1.02 = .916$$
$$A = .47 \times 1.2 \qquad = \underline{.565}$$
$$1.48$$

$$\text{Then } M' = \frac{3.44 \times 1.5\ (299)}{1 + \left(\frac{1.5 \times .548 \times .2}{.45}\right)12} = 287,$$

and $t' = 121.5$

It is evidently unnecessary to make another and closer approximation to Q.

It will be noticed that a difference of about twelve per cent. in the value of Q only made a difference of two per cent. in the results. So it is quite unnecessary to be too particular about the value of Q, and the smaller the pipe the less effect does an error in Q have.

The following values of C for different materials were determined by Péclet:

Plaster	3.44	Hempen Canvas	.418
Oak	1.70	Smooth White Paper	.346
Walnut	.86	Cotton Wool	.323
Fir	.75	Sheep Wool	.323
Powdered Charcoal	.637	Eiderdown	.314
Wood Ashes	.484	Blotting Paper	.274

As far as the theory goes it evidently makes no difference whether the steam in the pipe is at rest or in motion, for the inner surface of the covering is at the same temperature in either case; namely that of the steam. Mr. Barrus made tests at the Manhattan Railway Co.'s new power house, in which he found the same rate of condensation from a covered pipe whether the steam was at rest or moving with a velocity of 18 feet per second. He also found this to be true for a bare pipe. (*Power*, Dec., 1901.)

As this theory is of such old origin it seemed best to apply it to a number of recent pipe covering tests and see how well calculations made by it would agree with their results.

Of course for any given pipe covering, we have to know the value of C, the coefficient of conductivity. This we can obtain by analyzing a test of the particular covering, then we can test the theory by calculating the loss of heat for the conditions obtaining in some other test of the same covering under different steam pressure, on a different sized pipe and with a different thickness of covering.

Or we may analyze this second test and determine C. If this is the same as the C of the previous experiment, we know that our calculation would have given the same loss of heat as the experiment.

It is this latter method that has been used here, and in this way a table of values of C for nearly all the well known coverings now on the market has been obtained.

By the aid of the formulas just given and this table, one may calculate the loss of heat from a covered pipe or boiler under any conditions.

METHOD OF DETERMINING THE VALUE OF THE COEFFICIENT OF CONDUCTIVITY C FROM AN EXPERIMENT.

As an example we will take Mr. Barrus' test on Keasbey's Magnesia on a 2-inch pipe with 1 inch thickness of covering, and 155 B. T. U. lost per sq. ft. of pipe surface per hour.

Temperature of steam, 365.2° F.

Temperature of air, 64.6° F.

The B. T. U. per foot run of pipe $= \dfrac{155}{1.61} = 96.2$.

The surface of covering in sq. ft. per foot of pipe $= 1.15$.

For a first approximation, take $Q = 1.7$.

Then $96.2 = 1.15 \times 1.7\,(t' - 64.6)$, (Eq. 2) and t', the temperature of the surface of the covering, equals 114°. The difference between this and the temperature of the air, 64.6°, is 49.4 degrees. We can now make a closer approximation to Q as follows: For a canvas covering, $K = .75$, and for a cylinder $4\frac{3}{8}$ inches in diameter, $K' = .56$ from Figure 4.

Then for a difference of 50 degrees Fahrenheit.

$$\begin{aligned} R &= .75 \times 1.2 \times 1.02 = .92 \\ A &= .56 \times 1.2 \qquad\quad\;\, = \underline{.67} \\ & \qquad\qquad\qquad\quad Q = 1.59 \end{aligned}$$

The above coefficients by which we have modified K and K^1 are taken from Figures 1, 2 and 3 for a difference of 50 degrees, and an air temperature of 65 degrees.

Then $96.2 = 1.15 \times 1.7\,(t' - 64.6)$ and $t' = 117$. $117 - 64.6 = 52.4$, which is so near 50 that we may take the value of 1.6 for Q as final.

We now know the temperatures of the inside and outside of the covering. Transposing our fundamental equation for the conduction of heat through a cylindrical covering, (Eq. 1) we get

$$C = \frac{M' \times N}{2\pi \times \text{difference of temps.}} \times 12$$

The temperature of the inside of the covering we know to be that of the steam, 365.2° F.; the temperature of the outer surface we have found to be 117; the difference is therefore 248.2°.

$$C = \frac{96.2 \times .61}{6.28 \times 248.2} \times 12 = .453$$

All the tests have been analyzed in this way and the value of C determined.

BARRUS' TESTS.

These tests are on a far larger scale than any previously made. Every precaution was taken to secure accuracy. The final results have not yet been published, but a preliminary description was published in *Power* of December, 1901, and the average of the maxima and minima condensations there given are used here.

Through the kindness of Mr. Barrus, I am able to say that those of these figures used here stand practically correct and the temperatures, thickness of coverings and areas of pipe surface have been given me by him for this paper.

The steam pressure was 150 pounds.

The pipes to which the covering were applied were 2-inch about 100 feet long, and 10-inch about 35 feet long.

The length of each test was about nine hours, but the tests were repeated day after day for a number of days, and the figures given are the average.

The tests were made in 1901.

Name of Covering.	Size of Pipe.	Thickness of Covering.	Temp. of Steam, Degs. Fahr.	Temp. of Air, Degs. Fahr.	B. T. U. per sq. ft. of Pipe Surface per hour.	Computed Value of *C*.
Asbesto-Sponge Felted	2″	1⅛″	364.8	60.7	145	.451
Do.	10″	1⅜″	364.8	62.8	85	.413
Magnesia	2″	1″	365.2	64.6	155	.453
Do.	10″	1 3/16″	365.2	66.0	103	.459
Asbestos Navy Brand	2″	1⅛″	365.2	64.6	176	.570
Do.	10″	1⅜″	365.2	66.8	112	.579

The covering was measured before being applied to the pipes.

The temperature of the steam is that corresponding to the pressure observed by a gauge.

In view of the fact that each figure in this table is an average of a number of tests, and considering the length of the test pipes and the care with which the experiments were made, we may confidently assert that having determined the value of *C* from an experiment with a given covering we may therefrom compute the loss of heat from any sized pipe with any thickness of covering, provided the steam pressure is the same as that obtaining during the experiment.

JACOBUS' TESTS.

An account of these tests by Professor Jacobus is to be found in the STEVENS INSTITUTE INDICATOR for July, 1901.

Name of Covering.	Thickness of Covering.	No. of Tests.	Steam Pressure, Lbs.	Temp. of Steam, Degs. Fahr.	Temp. of Air, Degs. Fahr.	B. T. U. per. sq. ft. of Pipe Surface per hour.	Computed Value. of *C*.
Hair Felt	.96″	2	55.4	302.8	71.4	89.6	.32
I. P. Remanit	.88″	6	57.2	304.5	73.3	100.3	.34
H. P. Remanit	1.3″	7	59.5	306.6	76.1	83.7	.37
Asbestos Sponge Felted	1.14″	3	62.0	309.2	79.4	59.7	.39
Magnesia	1.08″	3	64.2	310.9	81.6	69.8	.45
Asbestos Navy Brand	1.20″	3	62.0	309.2	79.4	69.9	.48
A-s-b-e-s-t-o-c-e-l	1.07″	1	54.2	301.8	77.2	143.0	.61
Asbestos Air Cell	.96″	1	55.9	303.3	72.3	165.5	.67
Asbestos Fire Felt	.99″	2	60.2	307.4	72.5	180.0	.74

The steam pressure was from 55 to 75 pounds.

The tests pipes were standard 2-inch pipes, 12 feet long.

The tests were about four hours long, but the figures here given are averages of several tests in most cases. The tests were made in 1901.

The values of C were for the most part worked up from the separate tests and averaged.

The "Remanit" coverings are of German origin. They were encased in canvas.

In the case of the "Hair Felt," a layer of asbestos paper $\frac{1}{32}$ of an inch thick was first bound around the pipe, over this was bound the hair felt, then a layer of paper, and outside of all a canvas covering.

BRILL'S TESTS.

These tests were published in Vol. XVI. of the *Transactions* of the American Society of Mechanical Engineers.

The steam pressure was 110 to 117 pounds.

The test pipe was a standard 8-inch steam pipe about 60 feet long.

The tests were about four hours long and the figures given here are in each case the average of three tests.

The tests were made in 1894 or 1895.

Name of Covering.	Thickness of Covering.	Steam Pressure, Lbs.	Temp. of Steam, Degs. Fahr.	Temp. of Air, Degs. Fahr.	B. T. U. per sq. ft. of Pipe Surface per hour.	Computed Value of C.
Magnesia	1.25″	110	344.1	66.3	106.6	.527
Rock Wool	1.60″	110	344.1	63.0	72.1	.395
Mineral Wool	1.30″	110	344.1	58.3	81.3	.381
Champion Mineral Wool	1.44″	113.3	346.1	74.3	86.1	.470
Asbestos Fire Felt	1.30″	111	344.7	79	133.5	.755
Manville Sectional	1.70″	112.3	345.5	78.3	93.4	.600
Hair Felt	.82″	117	348.3	69	117.9	.396
Riley Cement	.75″	116.3	347.9	74.3	260.8	1.200
Fossil Meal	.75″	115	347.1	75.3	238.8	1.050

The "Riley Cement" and "Fossil Meal" were mixed with water and plastered on the pipe.

The "Hair Felt" was bound very tightly around the pipe and had no canvas covering. It had a layer of asbestos paper under it. Its tightness would increase its conductivity, and furthermore it had no canvas covering, which throws a doubt as to what value to asign to K for the radiation. This would be sufficient to explain the increased value of C over that found in Prof.

Jacobus' tests without assuming a different quality of "Hair Felt."

The three coverings, "Rock Wool," "Mineral Wool" and "Champion Mineral Wool," are all mineral wools, and it is interesting to note that the chemical composition of the first two is almost identical, both having about 18 per cent. of magnesia, while the "Champion Mineral Wool" has only 3 per cent.

130 POUNDS STEAM PRESSURE TEST.

The results of this test have not previously been published. The writer was personally connected with it and worked up the original report.

The test pipes were 2-inch standard steam pipes 80 feet long.

The test was forty-eight hours long, and was made in 1896.

Name of Covering	Thickness of Covering.	B. T. U. per sq. ft. Pipe Surface per hr.	Computed Value of *C*.
Magnesia	1.09″	155.8	.534
Manville	1.31″	157.0	.606
Asbestos Fire Felt	1.00″	198.0	.680

The average steam pressure was 128.7; temperature corresponding, 354.7; average temperature of air 80.1.

NORTON'S TESTS.

These tests were published in the *Transactions* A. S. M. E., Vol. XIX. They were made in 1896-1897.

They are interesting inasmuch as the pipes under test were filled with oil, heated by an electric current passing through a coil. The oil was agitated by two small propellers.

We have already shown that the outside of a covered pipe carrying steam takes the temperature of the steam, and in these experiments it would take the temperature of the oil, and for equal temperatures the loss of heat would be the same. The following computed values of C bear out this opinion fairly well:

Name of Covering.	Size of Pipe.	Thickness of Covering.	Temp. of Steam, Degs. Fahr.	Temp. of Air, Degs. Fahr.	B. T. U. per sq. ft. Pipe Surface per hour.	Computed Value of *C*.
Magnesia	4″	1.12″	388	72	147	.52
Manville	4″	1.25″	388	72	143	.55
Asbestos Air Cell	4″	1.12″	388	72	166	.60

The corresponding steam pressure would be 201 pounds.

Two test pipes were employed, one 4 inches in diameter, and one 10 inches; both were vertical and 36 inches in length.

In the calculations in this case, the value of K' was taken from Figure 5, instead of from Figure 4, as in the other tests.

Further experiments with the 10-inch pipe with great thicknesses of coverings were vitiated by the fact that the ends of the pipes emit heat, according to a very different law from that obtaining for the cylindrical portion, and further, the ends being covered by a thickness equal to that on the cylindrical portion the length of cylindrical surface is increased. This seriously impairs the value of Mr. Norton's conclusions as to the relative advantage of increased thickness of covering.

Mr. Norton also made a number of tests on the loss of heat from his test pipes without any covering.

An analysis of these reveals inconsistencies which are easily explained by a study of Péclet's experiments on the conductivity of metals. Mr. Norton's agitating arrangement though sufficient for the slow loss of heat from a covered pipe was quite inadequate for the loss from a bare pipe and the results of his experiments were falsified by the resistance of the oil. We may however draw certain general conclusions that are useful.

By exposing one of his bare pipes to the draft from an electric fan the loss of heat was increased by about 50 per cent. The radiation would be unaffected by the draft, but the air contact loss, which in still air was about 40% of the total loss, must have been increased by 120% or to more than double its value in still air.

Now if we take the case of the magnesia covering in still air we have by the experiment a loss per sq. ft. of pipe of 147 B. T. U. per hour. In this case the value of K (radiation) was .96 and K' (air contact) .73. If we increase K' by 120% we have K' equal to 1.6, K remains .96 as before, and the computed value of the loss per square foot of pipe would become 166, an increase of 13%.

Mr. Norton stated during the discussion that in no case had he been able to increase the loss with any of the covered pipes more than 10% by the draft from an electric fan. This agreement between our calculation and his experiment gives us some idea of what allowance to make for any covering when in a position exposed to strong drafts.

SUMMARY OF TESTS

TABLE OF VALUES OF C

Name of Test.	Barrus	Barrus	Jacobus	Brill	130 lbs	Norton
Year of Test	1901.	1901.	1901.	1895.	1896.	1896.
Size of Pipe	2 ins	10 ins	2 ins	8 ins	2 ins	4 ins
Length of Pipe, about	100 ft	30 ft	12 ft	60 ft	80 ft	3 ft
Pressure of Steam	150 lbs	150 lbs	55-75 lbs	110-117 lbs	129 lbs	200 lbs
Name of Covering			*Values of C.*			
Hair Felt			.32	.40		
Int. Press. Remanit			.34			
High Press. Remanit			.37			
Mineral Wool				.38		
Rock Wool				.40		
Asbestos Sponge F'l'd	.45	.41	.39			
Magnesia	.45	.46	.45	.53	.53	.52
Champion Min. Wool				.47		
Asbestos, Navy Brand	.57	.58	.48			
Manville Sect				.60	.61	.55
A-s-b-e-s-t-o-c-e-l			.61			
Gast's Ambler Asbestos Air Cell			.67			.60
Asbestos Fire Felt			.74	.76	.68	
Fossil Meal				1.05		
Riley Cement				1.20		

Before analyzing the meaning of the results shown in this table, it is best to recur to the method by which these figures were obtained. We have already shown this using as an example Mr. Barrus' test of magnesia covering on a 2-inch pipe.

We will now assume an error of 5 per cent. in the condensation, then instead of 96.2 B. T. U. per foot run we will have 101.

$$\text{Then } 101 = 1.15 \times 1.6\,(t' - 64.6)$$
$$\text{and } t' = 120 \text{ instead of } 117.$$

$$\text{Then } C = \frac{101 \times .61}{6.28 \times 245.2} \times 12 = .481$$

We found before that $C = .453$. An error of 5% then in the experiment causes an error of $6\frac{2}{10}$ per cent. in the computed value of C.

Our object in examining these experiments was to prove that Péclet's theory was in agreement with them, or perhaps it is better to say that we wish to prove that, having determined by an experiment the value of C we were then in a position to compute by Péclet's theory, the loss of heat from any sized steam pipe under any pressure of steam, with any reasonable thickness of the given covering, and with any usual temperature of external air.

Let us now examine the figures of the table.

Considering the large scale on which Mr. Barrus' tests were made, the number of tests taken to give an average figure, and the care with which the tests were made, we are justified in holding that the theory is amply proven for different sized pipes, and different thicknesses of coverings under the same steam pressure, by the Barrus tests on "Asbesto-Sponge Felted," "Magnesia" and "Asbestos Navy Brand." That the theory takes care of any difference of steam pressure is proven first of all by Barrus' and Jacobus' "Magnesia" and "Asbesto-Sponge Felted," secondly by Brill's, 130 lbs'. and Norton's "Magnesia," by Jacobus' and Brill's "Fire Felt," and by Brill's and 130 lbs'. "Manville."

Each of these examples are additional proof that different pipe sizes and different thicknesses of coverings are perfectly taken care of by the theory.

The only discrepancy that I think worth noticing is that between Barrus' and Jacobus' "Asbestos Navy Brand."

There is quite a difference between the values of C for "Magnesia" tested in 1895 and in 1901. I think it is fair to assume that the material has been improved in that time.

The discrepancy in the case of "Hair Felt" has already been explained. Prof. Jacobus' figure is no doubt the correct one.

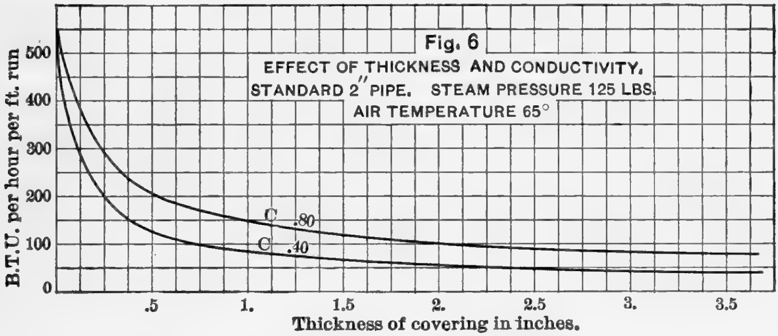
Pipe coverings are not absolutely homogeneous, and experiments of any kind are seldom in perfect agreement. Taken altogether the experimental proof is very strong.

APPLICATIONS OF THE THEORY.

Effect of Thickness and Conductivity.—Figure 6 shows clearly the very great saving of heat that is obtained by even very moderate thicknesses of coverings. It also shows how quickly the economical limit of thickness of a covering is reached.

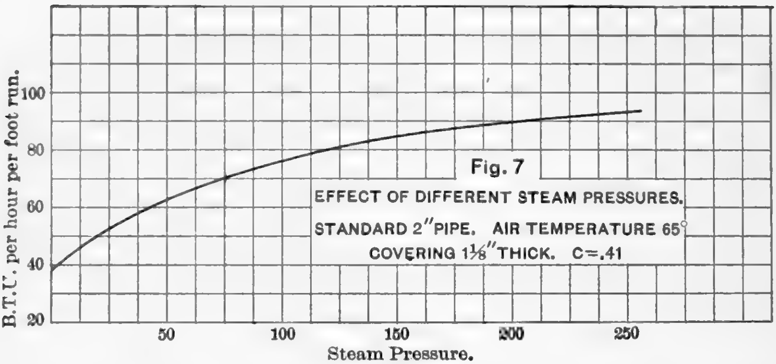
In regard to conductivity, we see that halving this for a covering one inch thick, a usual thickness for this size of pipe, reduces the loss from 150 to 85, a reduction of forty-three per cent. instead of fifty. This is because the surface resistance to loss is the same in both cases. In all these examples the coverings are supposed to be surrounded by a thin canvas jacket.

It is of interest, though perhaps of no particular practical value, to note that if we employ a pipe covering having a conductivity greater than 6.00, which is not so very much greater than that of some plaster, the loss of heat will increase with the thickness of the covering, and may even be greater than for the bare pipe. This is because the action of the increased surface outweighs the feeble resistance of the covering.



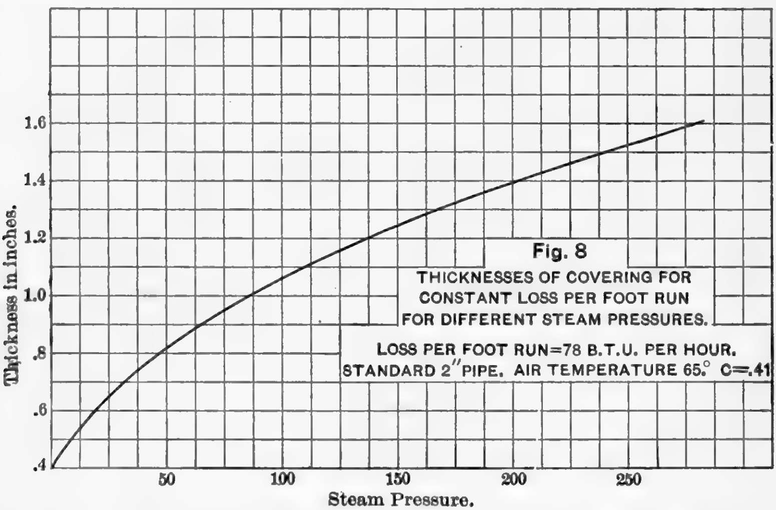
The Effect of Different Steam Pressures.—Figures 7 and 8 should prove of value in the judicious choice of thickness of covering for very high steam pressure on the one hand and for the conveyance of hot water on the other.

The Effect of Different Sized Pipes.—A little consideration will show that if, in our efforts to stop the escape of heat by an increase of thickness, we at the same time present a larger area for its passage, our gain will be but slight. This is precisely what happens with thick coverings on small pipes, as shown in Figure 9. We see that a one-inch pipe requires one and three-quarters inches of covering to keep the loss per square foot on its surface the same as for a ten-inch pipe with only eight-tenths of an inch of covering. This Figure is an excellent example of the danger of interpreting a theory from a too narrow point of view. It evidently indicates that coverings for large pipes should be thinner

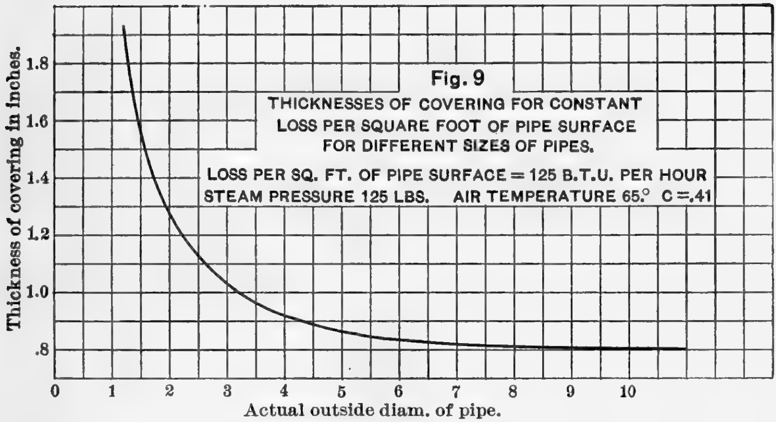


than for small ones. The usual practice of the manufacturers of pipe coverings is directly opposed to this, and there are very good reasons for their course.

In the first place the cost of a large pipe line warrants the expenditure of sufficient money on the covering to have it of a



liberal thickness, and thus to secure a low heat loss. Secondly the bulk of the small pipes would be very objectionable in many cases if they were so thickly covered and the expense of covering would be out of all proportion.



The useful lesson to be drawn from Figure 9 is that the loss of heat from small pipes will always be large in proportion to their surface, and it is also to be remembered that the proportion of surface to weight of steam passed is much greater for small pipes than for large.

In conclusion it may be mentioned that the very important quantities of durability and non-inflammability of a covering are entirely outside of the scope of these notes.

NOTE.—The table at the end of the book makes the solution of practical problems by the formulas of page 7 much simpler. It obviates the use of logarithms and much calculation for ordinary thicknesses of coverings on standard wrought iron steam pipes.

THE LOSS OF HEAT FROM BARE STEAM PIPES

In a previous paper it was shown that Péclet's theory of the loss of heat from a surface maintained at constant temperature gives results in agreement with extensive practical tests of the loss of heat from covered steam pipes.

The purpose of the present paper is to show that the theory is of the same practical value for bare steam pipes.

The subject is chiefly of value to manufacturers of pipe coverings, since they are not infrequently required to guarantee a certain saving by the use of their covering over the loss that would take place with a bare pipe, and it was at the suggestion of one of these gentlemen that this second paper was undertaken.

In tests of pipe coverings, one of the test pipes is usually tried bare, and the result used for determining the saving due to the various coverings.

Any unreasonable claims on the part of the manufacturers are, therefore, liable to prompt exposure, and some reliable method of estimating the saving due to their covering under the particular circumstances of the test is evidently of value to them.

When a metal steam pipe of customary thickness is filled with steam at rest or in motion at ordinary velocities there is a constant escape of heat through the walls of the pipe. This heat traverses the pipe by virtue of the conductivity of the metal and on reaching the outer surface a portion is radiated to the surrounding objects and the remainder is carried off by the contact of the surrounding air.

The conductivity of all the metals is so high that we may without perceptible error neglect this part of the process and simply assume the temperature of the outer surface of the pipe to be the same as that of the steam within. We need only consider then the manner of the escape of heat from the surface.

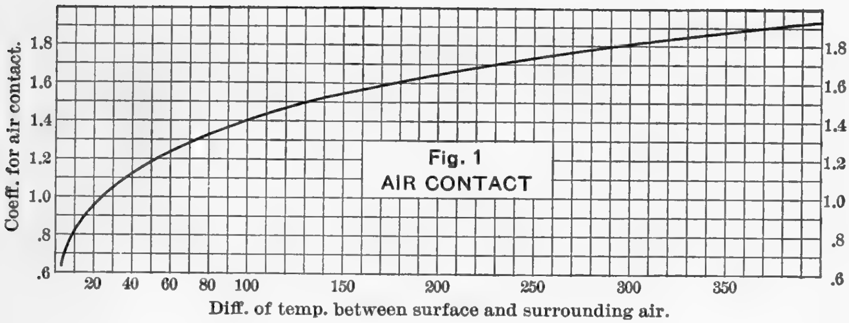


Fig. 1
AIR CONTACT
Coeff. for air contact.
.6
.8
1.0
1.2
1.4
1.6
1.8
20
40
60
80
100
150
200
250
300
350
Diff. of temp. between surface and surrounding air.

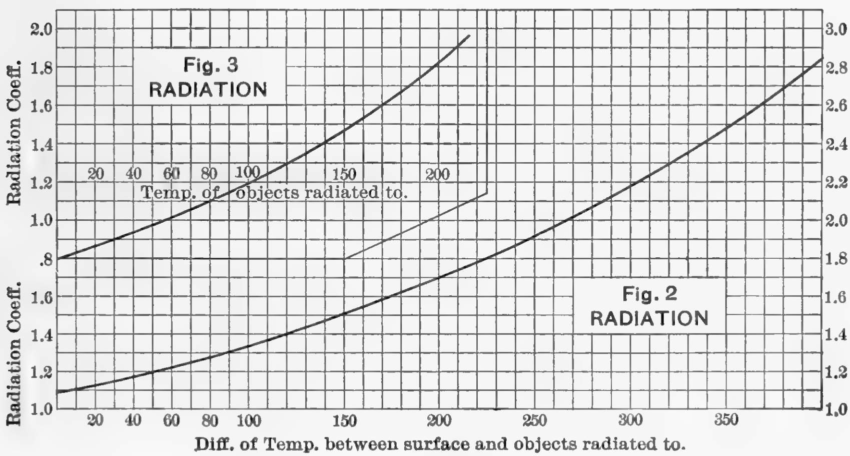


Fig. 3
RADIATION
Radiation Coeff.
.8
1.0
1.2
1.4
1.6
1.8
2.0
20
40
60
80
100
150
200
Temp. of objects radiated to.
Fig. 2
RADIATION
Radiation Coeff.
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
20
40
60
80
100
150
200
250
300
350
Diff. of Temp. between surface and objects radiated to.

The loss of heat by air contact depends on the diameter of the pipe, on its position, whether vertical or horizontal, and on the difference of temperature between its outer surface and the surrounding air. We may express it by the following equation:

Loss by air contact in B. T. U. per square foot per hour $= K' \times C \times$ diff. of temp., in which K' is the term affected by the diameter and position of the pipe and is given by Figs. 4 and 5. C is a coefficient determined by the amount of the difference of temperatures and its value is given by Fig. 1. The difference of temperatures is that of the steam and the surrounding air.

The loss of heat due to radiation depends on the nature of the surface of the pipe, on the difference of temperatures and on the temperature of the surrounding objects thus:

Loss due radiation in B. T. U. per sq. ft. per hour $= K \times C' \times C'' \times$ diff. of temp., where K is a number depending on the nature and condition of the surface of the pipe, C' a coefficient depending on the amount of the difference of temperatures, its values being given by Fig. 2, and C'' a coefficient, given in Fig. 3, depending on the temperature of the surrounding objects. The temperature of the surrounding objects we must usually consider to be the same as the temperature of the surrounding air.

Summarizing we have:

Loss of heat in B. T. U. per sq. ft. per hour

$= (A + R) \times$ diff. of temp.

$= [(K' \times C) + (K \times C' \times C''] \times$ [diff. of temp.]

A study of this formula will show that all its parts except K are rigorously fixed by Péclet's deductions from his experiments. For that matter K is given by his experiments within narrow limits and might be expected to have the value .64.

There are, however, enough reliable experiments on a large scale to make it preferable to deduce K directly from them.

The table on the following page gives the results of a number of careful and reliable tests, most of which were on a large enough scale to give results of assured practical value.

In the previous paper references will be found to the published data of these tests.

Prof. Jacobus has kindly furnished additional data in regard

EXPERIMENTS ON THE LOSS OF HEAT FROM BARE STEAM PIPES.

Name of Experimenter.	Approx. Duration in hours.	No. of tests averaged.	Size of pipe.	Square feet of pipe surface.	Pressure of Steam.	Temp. of Steam.	Temp. of Air.	Difference of Temp's.	Lbs. of steam condensed per sq. ft. per hour.	B. T. U. per sq. ft. per hr. per 1 deg.	Value of *K*.
Barrus	3.3	7	2″	63.57	82.2	325.2	56.6	268.6	.915	3.01	.904
"	4.3	7	2″	63.92	149.6	365.4	63.2	302.2	1.150	3.25	.895
"	2.7	3	10″	98.33	149.3	365.3	73.6	291.7	1.085	3.18	1.006
Hudson-Beare . . .	—	1	3.53*	8.13	135.0	358.0	67.0	291.0	1.050	3.10	.915
130 lbs.	48	1	2″	50.66	128.7	354.7	80.1	274.6	.994	3.13	.856
Jacobus	—	1	2″	7.63	53.4	300.8	71.2	229.6	.707	2.78	.829
Brill	1	4	8″	135.4	110.5	344.5	75.5	269.0	.834	2.71	.843

*Actual outside diameter.

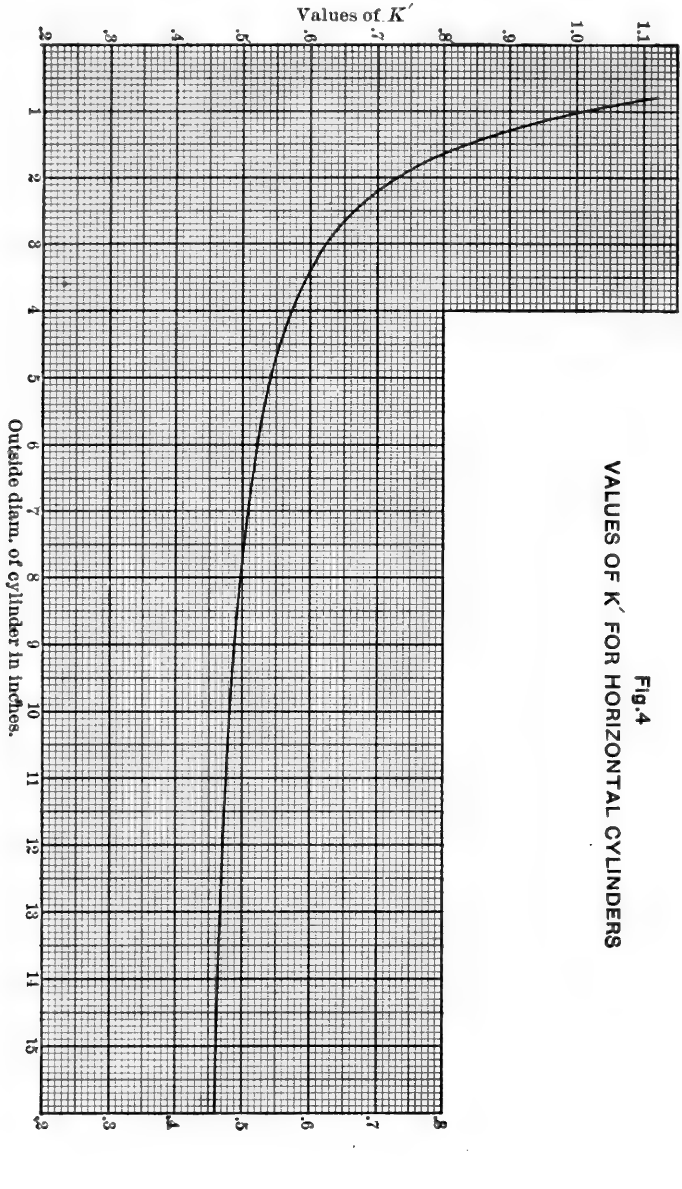


Fig.4
VALUES OF K' FOR HORIZONTAL CYLINDERS

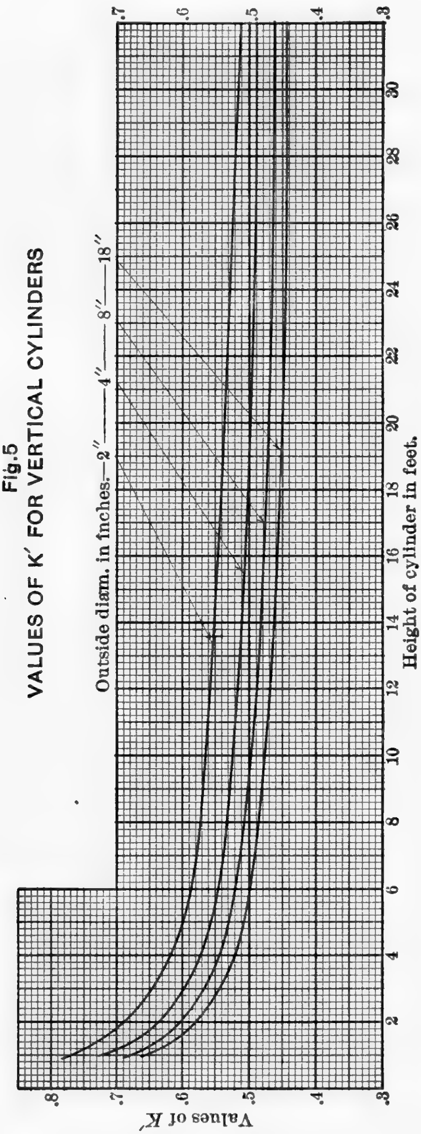


Fig.5
VALUES OF K′ FOR VERTICAL CYLINDERS

to his test and some additional data in regard to Mr. Barrus' tests has also been obtained.

The results of the tests are shown graphically in Fig. 6. The curves drawn thereon were computed as follows:

Steam pressure 100 lbs., temperature 338° Fahr., temperature of air 65° Fahr. Difference of temperatures 273°. Outside diameter of pipe 2.38 ins.

Taking the value of K at .87 we have

$$R = .87 \times 1.04 \times 2.03 = 1.83,$$

the coefficient 1.04 for air temperature having been found from Fig. 3, and the coefficient for difference of temperatures from Fig. 2.

The coefficient K' we find from Fig. 4, since the test pipes were all horizontal, to be .68, choosing from Fig. 1 the proper coefficient for difference of temperatures we have,

$$A = .68 \times 1.77 = 1.20.$$

Then the loss in B. T. U. per square foot per hour per 1° difference of temperatures between the steam and the surrounding air,

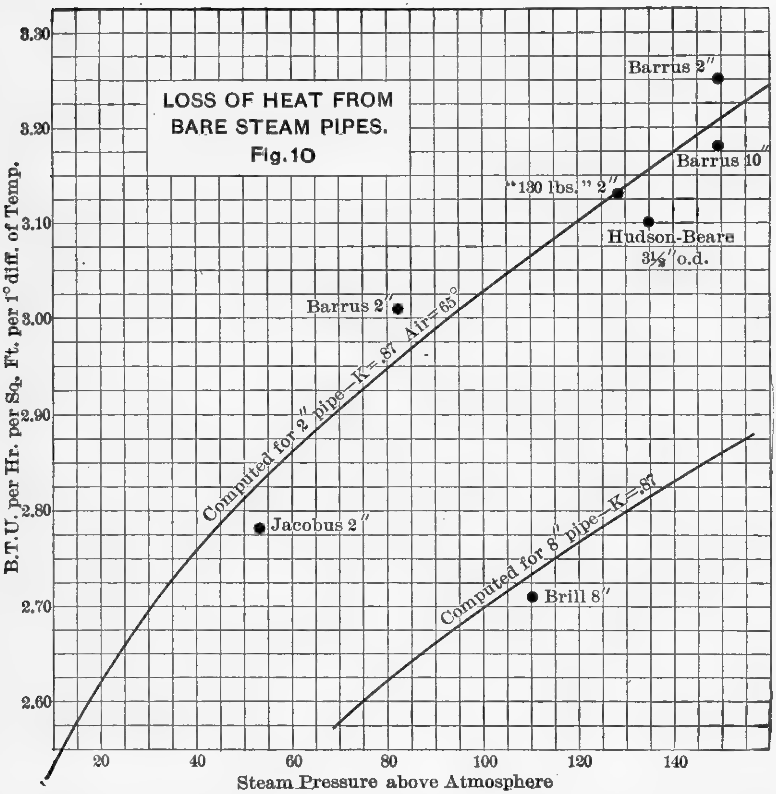
$$= R + A = 1.83 + 1.20 = 3.03.$$

Proceeding thus for several different steam pressures the curve for the 2-inch pipe was drawn, and that for the 8-inch pipe was constructed in the same way.

The curve for the 2-inch pipe agrees within less than two per cent with all the experiments on that size of pipe. The curve for the 8-inch pipe agrees with the only experiment on that sized pipe that we have.

It is, however, to be noted that Mr. Barrus' experiment on the 10-inch pipe is not at all in agreement with the theory. This experiment was made on two 10-inch pipes parallel to one another and only 24 inches distant between centers, certainly not the very best arrangement for a test of this kind. Although the radiation would be somewhat decreased the air contact action of the ascending currents of air might easily have been considerably increased.

We may say that Fig. 10 demonstrates that for a given size of pipe the theory takes care of any steam pressure between zero and 150 pounds. Brill's test would show that the theory also



allows for the different loss of a different size of pipe, but Barrus' test on the 10-inch pipe is equally strong evidence that it does not. Hudson-Beare's test also agrees with the theory.

Fortunately we are not entirely dependent on these tests for this point. The previous paper on the "Loss of Heat from Covered Steam Pipes" showed by a large number of tests that the theory did in that case most certainly allow correctly for different outside diameters of coverings. Now, the loss of heat from the surface of a bare pipe must be governed by the same laws as the loss of heat from the surface of a pipe covering, and we may therefore conclude that the theory does cover the loss from a pipe of any diameter.

We have then a simple means of accurately estimating the loss of heat from a steam pipe or boiler.

I am at a loss to explain why the experiments require the value of K to be .87 when Péclet's experiments point to a value of .64. It may have been because his tests were made with very much smaller differences of temperature.

The effect of the condition of the surface of the pipe may be inferred from the following values found by Péclet:

Ordinary sheet iron	.567
Rusty sheet iron	.688
New cast iron	.650
Rusty cast iron	.688

The effect of air currents is very marked in the case of bare pipes. Mr. Norton in his experiments found that the draft from an electric fan increased the loss by one-half in the case of a vertical 4-inch pipe.

Mr. Barrus showed conclusively by several tests that the loss of heat from a bare pipe is the same whether the steam therein is at rest or in motion at ordinary velocity.

EMISSION AND TRANSMISSION OF HEAT*

CHAPTER I.

EMISSION OF HEAT FROM A SURFACE MAINTAINED AT A CONSTANT TEMPERATURE.

775. The case under consideration is that of a pipe heated within by steam, and with its outer surface exposed to the air; that of a vessel full of warm water, and so on. The quantity of heat emitted by a surface maintained at constant temperature, and exposed to the air depends on the area of its surface, on its form, on its temperature, and on that of the air to which it is exposed. It is important to know the quantity of this heat in heat units, per unit of surface, during unity of time, as a function of the elements which cause it to vary, at least for the cases which ordinarily occur in practice.

In order to understand how this quantity of heat emitted may be determined, consider the case of a metallic vessel full of warm water; the metals being very good conductors of heat, the exterior surface of the vessel will be at the temperature of the water which it contains, let the weight of water, augmented by that of the vessel, multiplied by its specific heat, be P kilograms, S the area of the surface of the vessel in square meters, $O° C$ the temperature of the surrounding air, θ the time in seconds which is required for the water to cool from $T°$ to $T-1$ degrees.

The quantity of heat units lost during the time θ is evidently equal to P, and ought to be sensibly the same as that quantity which would have escaped from the vase in the same time if the temperature had been constant and equal to the mean of T and $T-1$, that is to say to $T-\frac{1}{2}$. According to this the quantity of heat M which the surface of the vessel would emit per hour per square meter, if the temperature were maintained at $T-\frac{1}{2}$ would be

$$M = \frac{P}{S} \times \frac{3600}{\theta} = \frac{1}{\theta} \frac{P \times 3600.}{S}$$

* From "Traité de La Chaleur" by E. Péclet.

Thus, by observing the intervals of time θ, θ', θ'', and so on, which correspond to successive coolings of one degree, one may therefrom compute the quantities of heat which would be emitted per hour per square meter for the corresponding excesses of temperature. It then remains to find by trial the law which these results follow expressed as a function of the excess of temperature.

776. When a vessel filled with warm water cools, we call the ratio between the infinitely small variation of temperature dt, and the time $d\theta$ in which this variation takes place, the rate of cooling thus, we have $v = \frac{dt.}{d\theta}$ Pdt represents the quantity of heat emitted in the time $d\theta$.

If the temperature of the vessel is kept constant, the quantities of heat emitted during equal intervals of time will also be constant, and that quantity emitted in unity of time will evidently equal $P\frac{dt}{d\theta}$ or Pv.

Since the second represents unity of time we have $M = v\frac{P \times 3600}{S}$.

Making $v = \frac{1}{\theta}$ which is to assume that the rate is constant during the cooling through one degree, we get the same value of M as found in 775.

777. *Newton's Law.*—Newton's hypothesis was that the rate of cooling in air was proportional to the excess of the temperature of the body above that of the air, and his formula was

$$v = qt$$

t being the excess of temperature and q a coefficient varying with the nature of the body.

This law is, however, inexact, the rate of cooling varying much more rapidly.

Dulong and Petit's Laws.—Dulong and Petit have made numerous experiments on the cooling of the thermometer placed in a closed vessel, maintained at a constant temperature by a water bath and filled with different gases under different pressures. These skilful physicists have established the following facts:

1st. The cooling of a body results from its radiation and from the contact of the surrounding gas.

2d. The rate of cooling due to radiation is independent of the substance of which the body is composed; but its absolute value varies with the nature of the surface of the body.

It is represented by the formula,

$$v = ma^{\theta}\,(a^{t} - 1)$$

in which m is a number depending on the nature of the surface, a the number 1.0007, θ the temperature of the surroundings and t the excess of the temperature of the body over that of the surroundings in degrees Centigrade.

3d. The rate of cooling due to the contact of the surrounding gas is also independent of the substance of which the body is composed, but its absolute value is independent of the nature of the surface; it depends solely on the form of the body and the excess of its temperature over that of the surroundings.

This rate for air at 760 *mm.* pressure is given by the formula

$$v = nt^{1.233}$$

in which n is a number varying with the form and the extent of the surface of the body, and t the excess of temperature of the body above that of the surrounding air in degrees Centigrade.

779. *New Experiments.*—While admitting the exactness of these laws, the formulas which represent them are of no service as long as the coefficients m and n are unknown for surfaces of different natures and for bodies of different forms. I may add that Laprévotaye and Desains have found, in certain cases, results that do not at all agree with the above formulas.

I have therefore thought it best to take up the question again, but limiting it to the study of the cooling of a body in air under ordinary pressure and in a chamber with dull walls; for the cooling of a body in different gases, under different pressures and in a chamber with gilded walls, is a purely speculative question which never occurs in practical applications.

780. There will be found at the end of this book the details of the apparatus and the methods of calculation employed in the experiments; I shall here confine myself to a general description and to the setting forth of the results arrived at.

781. Experiments, for the purpose of finding the absolute

values of rates of cooling, can not be made simple on thermometers. I have used spheres of thin brass with diameters ranging from two inches to twelve inches, a number of cylinders with diameters of one and a quarter inches to twelve inches and lengths of two to twenty inches, and also several rectangular vessels of different dimensions.

All of these vessels have been employed successively bare and covered with different substances. The water which they contained was continuously agitated. The temperatures were measured by very sensitive thermometers. Intervals of time were determined by means of a Bréguet counter.

The vessels were placed in an open chamber having a double wall. The interval between the walls was filled with water, and the contained air was constantly renewed through passages which gave to the entering air the temperature of the walls of the chamber.

782. Figure 149 represents a vertical section of the constant temperature chamber, figure 150 a plain of the same. *ABCDEF* and *A′ B′ C D′ E′ F′* are two cylinders of sheet iron plated with lead. They are concentric and the intervening space is filled with water.

This envelope is formed of two halves separated in a vertical plane and held together by suitable fastenings. The interior cylinder is 39 inches high, and 32 inches in diameter; the interval between the two cylinders is 1¼ inches and the water contained in this interval is frequently agitated by horizontal annular plates, to which are attached vertical iron rods projecting through the little stuffing boxes *GG*.

The temperatures of the water in each half of the envelope is given by thermometers inserted at *I* and *I*. *KLM* and *K′ L′ M′* are two vertical enclosures fastened on the outside of each half of the chamber. They are open above and communicate below with the openings *NP* (fig. 149) fashioned in the lower part of each of the two halves of the chamber. The outer wall of these enclosures is made of wood. They contain throughout their height, strips of sheet iron soldered perpendicular onto the outer surface of the chamber, each 4 inches high, and extending to the wooden outside of the enclosure, and the strips of one horizontal row are placed midway between those of the two adjacent rows. Similar strips are placed in the opening *N* and *P*. *QR* and *Q' R'* are two sealed half cylinders of tin full of water at the oridinary temperature, they serve to close, to the desired extent, the opening *AF* of the chamber. *ST* is an adjustable tripod bearing three glass tubes terminated by wooden stoppers, into which penetrate copper stems soldered to the vessel of which the rate of cooling is to be determined.

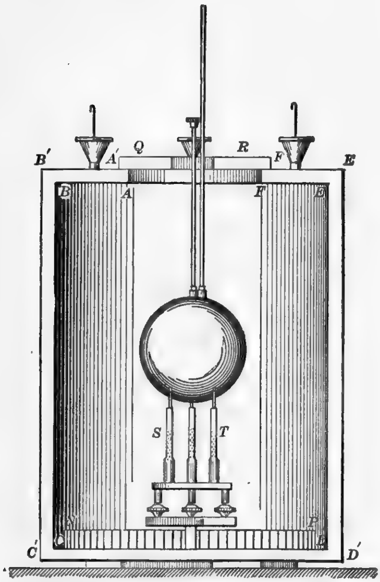


Fig. 149

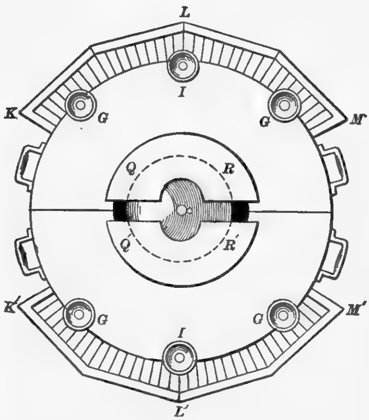


Fig. 150

783. Figures 151 and 152 show a vertical and horizontal section of a spherical vessel and its agitator.

The plates which agitate the water are carried by six pieces of iron wire in the shape of a semi-circle. These are attached below to the axial stem and above to a small horizontal ring which allows of the insertion of the thermometer through the tubular orifice shown. The cylindrical vessels of large diameter are arranged in the same way (fig. 153 and 154).

When the cylinders are of small diameter the agitator is placed on one side (fig. 155 and 156).

784. I show in figures 157 to 161 the different methods of

supporting the vertical and horizontal cylinders in a frame placed within the chamber. The object of these arrangements is to render the cylinders perfectly motionless in spite of the movements of the agitator. The frames are of iron or brass, the stems *a*, *a*, *a*,

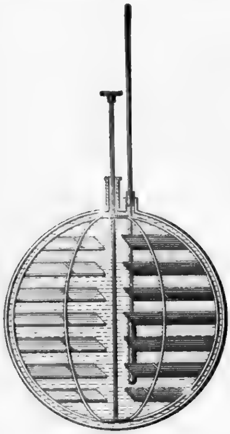


Fig. 151.

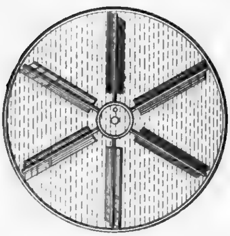


Fig. 152.

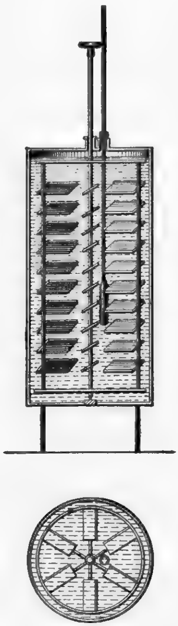
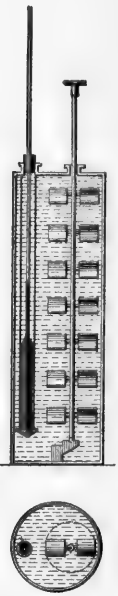


Fig 153 and 154.



Figs. 155 and 156

are very thin and of fir wood; they project into very small metallic appendices soldered to the vessels. When the cylinders are placed horizontally, the stem of the agitator turns in a cork which closes the tubular opening. There is a little play between the stem and cork, but the water does not escape on account of the expansion of the small quantity of air remaining in the vessel. This expansion is due to the contraction of the water by cooling.

Figure 162 is a section of a cylindrical vessel, with hemispherical ends, provided with two agitators.

When the vessels are long and of small diameter, cylinders of iron filled with mercury are employed, an agitator is no longer necessary, and a thermometer with a long reservoir inserted in the vessel, gives its temperature accurately.

785. Figure 163 shows the little apparatus used in reading the thermometers. *ab* is a small plate covered with white paper, and bearing at the middle of its height two projecting rods, one on each side of the stem of the thermometer. These rods are parallel to one another and perpendicular to the plate *ab*. They have fastened upon them two hairs which determine a plane perpendicular to the stem of the thermometer and in which plane the eye of the observer should be placed.

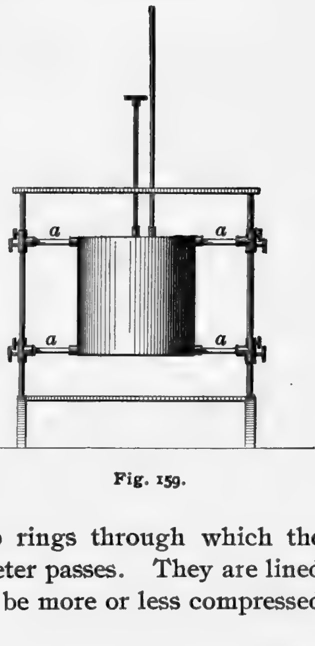
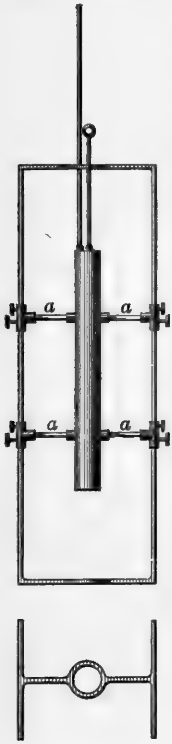


Fig. 159.

c and *d* are two rings through which the stem of the thermometer passes. They are lined with cork which can be more or less compressed by thumb screws.



Figs. 157 and 158.

This apparatus is necessary on account of the motion caused by the agitator which renders the use of a cathetometer impossible.

786. Figure 164 shows the apparatus used to refill the vessels at certain stages of their cooling, which is necessary in order that the cooling surface may remain constant.

An opaque vessel, in which the level of the water has descended, has to be refilled without taking it out of the constant temperature chamber and without spilling any water.

The apparatus consists of a glass tube *AB* open at both ends and provided with a reservoir *C*, at its side another glass tube *DEF*, bent over, and likewise open at both ends. The ends *B*

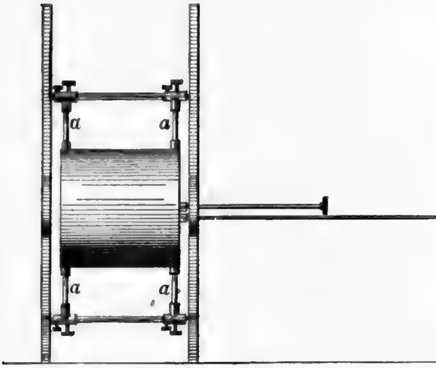


Fig. 160.

Fig. 161.

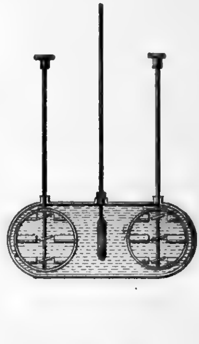


Fig. 162.

and *D* are at the same level. Both tubes are inserted at their lower ends in a stopper which enters freely into the tubular opening of the vessel, this stopper bears at its upper end a plate of brass of a diameter greater than the opening of the vessel, which allows the stopper to be inserted always to the same distance. When the stopper is put in, the point *B* is at the height which the liquid should reach. To fill the vessel the stopper closing the opening is removed, and is replaced by the stopper bearing the glass tubes; the reservoir *C* being full of water and the end *A* closed by a finger. The end *A* is then opened and the operator sucks on the tube *F*, and evidently when water appears in the tube *F*, the water level in the vessel will have reached the height *BD;* at this moment the extremity *A* is again closed, the apparatus is lifted out and the ordinary stopper replaced.

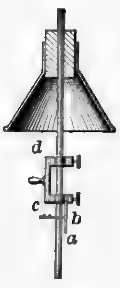


Fig. 163.

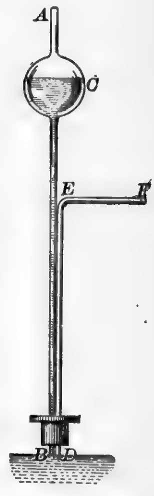


Fig. 164.

787. The mode of precedure was as follows: the vessel having been filled with hot water and placed upon its support the

constant temperature chamber was closed, the opening at the top for the escape of air was so adjusted that its area was approximately equal to that of a horizontal section of the vessel, the agitator within the vessel was turned continuously, and those of the chamber were put in motion from time to time.

The time required at a number of stages, for the thermometer to fall through a few divisions was observed. The temperatures indicated by the thermometer were reduced to what they would have been if the whole stem had been plunged in the water, on the assumption, proved both by experiment and calculation, that the stem was exactly at the temperature of the surrounding air.

788. From these experiments the rate of cooling can be readily deduced.

After obtaining the values of the rates of cooling v, and therefore (776) the values of M, the quantities of heat emitted, for excesses of temperatures ranging from 45 to 117 degrees Fahrenheit, I sought to connect them by some simple law, and found that they satisfied the following,

$$M = at(1 + bt)$$

This agrees perfectly with the formulas of Dulong and Petit within the limits of temperature mentioned above, and it results that these formulas are very probably exact up to an excess of temperature of 470° $F.$ as these two celebrated men have indicated.

Since cooling results from simultaneous radiation and contact of air, it is necessary to separate the effects of these separate causes, in order to determine the coefficients used in the formula. To do this I have employed the following method. Let us suppose that M represents the quantity of heat lost by a vessel coated with lamp black, M' that which is lost by the same vessel with a brilliant surface, A the quantity of heat lost by air contact, and which is the same for both surfaces, and R and R' the quantity of heat lost by radiation from the lamp black, and the metal respectively. Then

$$M = A + R;\ M' = A + \mathrm{R}', \text{ and it follows that}$$

$$M - M' = \mathrm{R} - \mathrm{R}'.$$

Let $R = cR'$ then the last equation becomes

$$M - M' = R'(c - 1) \text{ and } R' = \frac{M - M'}{c - 1} \text{ and as}$$

$M = at(1 + bt)$ and $M' = a't(1 + b't)$ the value of R' would be

$$R' = \frac{a - a'}{c - 1} t + \frac{ab - a'b'}{c - 1} t^2$$

Having thus obtained a general expression for the value of R', that for A is easily deduced from it since $A = M' - R'$.

I employed the following method in obtaining the ratio c of the radiations; it depends on one of Dulong and Petit's laws. Two metallic vessels, one side of each being a vertical plane, bare or covered with different materials, are placed with their plane faces opposite and parallel, and equally distant from a thermopile connected to a very sensitive galvanometer. One of the surfaces is maintained at a constant temperature while the temperature of the other is caused to vary until the effects produced on the thermopile are the same, that is to say until the needle of the galvanometer returns to zero. Designating by m and m' the radiating power of the two surfaces, by t and t' the excesses of their temperatures above θ, that of the thermopile, we have for the quantities of heat radiated according to Dulong and Petit $ma^\theta(a^t - 1)$, and $m'a^\theta(a^{t'} - 1)$, and as these quantities are equal, we deduce that

$$C = \frac{R}{R'} = \frac{m}{m'} = \frac{a^{t'} - 1}{a^{t'} - 1}$$

From all these experiments there result the following formulas.

789. The quantity of heat emitted by radiation to surroundings at a temperature differing but little from 12° C., and for excesses of temperature between 25° C. and 65° C. is given by the formula

$$R = Kt(1 + .0056t) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

K is a coefficient depending on the form and the dimensions of the body, t is the excess of temperature in degrees Centigrade.

790. The quantity of heat lost by contact of air in the same circumstances is given by the formula,

$$A = K't(1 + .0075t) \quad . \quad . \quad . \quad . \quad . \quad (b)$$

K is a coefficient depending on the form and the dimensions of the body, t is the excess of temperature in degrees Centigrade.

791. When the excess of temperature is but slight, one may neglect the terms of the second degree and we then have for the total quantity of heat emitted

$$M = R + A = (K + K') \; t = Qt$$

which is Newton's Law.

The formulas (a) and (b) have only been proven for excesses of temperature ranging between 45° F. and 117° F. for greater excesses of temperature we must employ Dulong and Petit's formulas.

We will therefore enunciate the formulas in a general form and give the values of the coefficients K and K' for different surfaces and bodies of different form according to the results of our experiments.

General Formulas Relative to the Emission of Heat in Air.

792. The quantity of heat emitted by a surface maintained at constant temperature depends on the radiation and the contract of air. If we designate by M the total quantity of heat emitted in a certain time, by R and A the quantities respectively due to radiation and air contract we have ;

$$M = R + A \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

793. *Heat Emitted by Radiation.*—The quantity of heat emitted by radiation, for unit surface and per unit of time, is independent of the form and size of the body—provided that its surface has no reëntrant portions ; it depends solely on the nature of the surface, on the excess of its temperature over that of the objects to which radiation takes place, and on the absolute value of the temperature of these objects.

794. When a body is surrounded by objects having dul surfaces, which is nearly always the case except in laboratory experiments, the quantity of heat R is given by the formula :

$$R = 124.72 \; K a^{\theta} \, (a^{t} - 1) \quad . \quad . \quad . \quad . \quad . \quad (2)^{*}$$

Where θ represents the temperature of the surrounding objects t the excess of the temperature of the surface above that of the surroundings, a a constant having the numerical value 1.0077,

* All the quantities in formula (2) and (3) are in French units.

and K a number depending on the nature of the surface of the radiating body.

Values of K for different surfaces. In B. T. U. per hour per square foot per 1° F. excess of temperature.

Polished silver	.027	Zinc	.049
Silvered paper	.085	Polished tin	.044
Polished brass	.053	Tin plate	.086
Gilded paper	.047	Sheet iron polished	.092
Polished copper	.033	Sheet iron leaded	.133
Cast iron—new	.649	Sheet iron (ordinary)	.567
Cast iron rusted	.688	Sheet iron rusted	.688
Glass	.596	Building stone	.737
Powdered chalk	.680	Plaster and brick	.737
Saw dust	.723	Wood	.737
Powdered charcoal	.700	Woolen cloth	.753
Fine sand	.741	Calico or canvas	.747
Oil paint	.759	Silk	.759
Paper	.772	Water	1.087
Lamp black	.820	Oil	1.482

795. For paper and cloth, color has no influence. It appears from this table that powdered materials have very nearly the same emissive power. Masson has already recognized that all substances in a very finely powdered state, obtained by precipitation and not crystallized, have the same emissive power.

796.*

797. *Heat Transmitted by Air Contact.*—The loss of heat arising from air contact is independent of the nature of the surface of the body, and of the absolute temperature of the surrounding air; it depends solely on the excess of the temperature of the body over that of the surrounding air, and on the form and dimensions of the body.

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* The tables given by Péclet in this paragraph are here replaced by the curves of figures 2 and 3, page 21.

It is more convenient, as will be apparent later on, to use Newton's Law for computing the loss of heat from a given surface and to modify the values of K given in the table above by coefficients obtained from formula (2) shown graphically in figures 2 and 3.

Figure 2 gives the coefficients by which K must be multiplied for different excesses of temperature. The product thus obtained is multiplied by a second coefficient obtained from figure 3 which corrects for different temperatures of the body radiated to.

This loss of heat per square meter per hour is given by the formula,

$$A = 0.552\,K'\,t^{1.233} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where t represents (in Centigrade degrees) the constant excess of the temperature of the body, over that of the surrounding air, and K' a number which varies with the form and dimensions of the bodies.*

798. For spherical bodies we have, in English units,

$$K' = .363 + \frac{1.048}{r}$$

where r = radius in inches.

799. For horizontal cylinders of circular section we have, in English units,

$$K' = .421 + \frac{.307}{r}$$

where r equals the radius in inches.†

800. In the case of vertical cylinders, the cooling depends both on their height and diameter, and

$$K' = .204\left(.726 + \frac{.216}{\sqrt{r}}\right)\left(2.43 + \frac{1.584}{\sqrt{h}}\right)$$

here r = radius in inches and h = height in feet.‡

802. For vertical plane surfaces, the value of K' is given by the formula

$$K' = .361 + \frac{.233}{\sqrt{h}}$$

where h is the vertical height of the surface in feet.§

804. Figure 1, page 21, gives the coefficients by which the value of K' obtained by the formulas above, must be multiplied in order to correct for the differences in temperature between the body and the surrounding air.

805. It is apparent from an inspection of Figures 1, 2 and 3 that Newton's Law is extremely inaccurate; the coefficients or the values of R and A, instead of remaining constant vary fof

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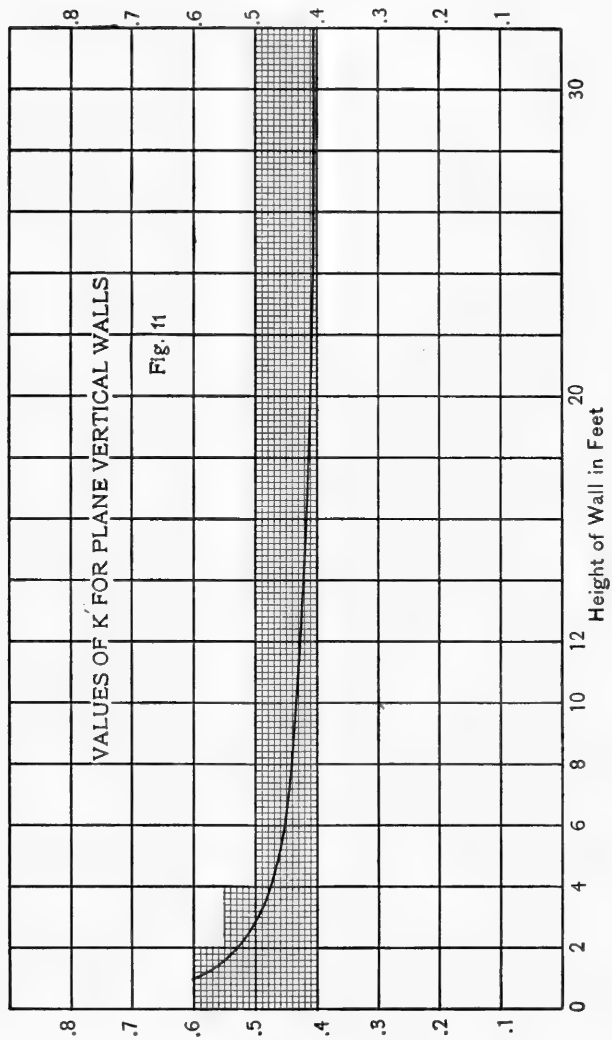
*It is important to note that by the temperature of the surrounding air is meant its temperature before it is in any way influenced by the heat emitted from the cooling body

† Figure 4, page 24 gives the values of K' for the horizontal cylinders up to 16 inches diameter.

‡ Figure 5, page 25, gives the values of K' for cylinders up to 18 inches diameter.

§ See Figure 11.



VALUES OF K' FOR PLANE VERTICAL WALLS

Fig. 11

excesses of temperature between 20° F. and 350° F., the first in the ratio of 1 to 2.2, the second in the ratio 1 to 2. Newton's Law is approximately true for small excesses of temperature only.

806. To sum up we have

$$M = R + A = 124.72\,Ka^{\theta}\,(a^{t} - 1) + 0.552\,K'\,t^{1.233}*$$

But we can always in practice calculate the valves of R and A by Newton's Law corrected by the coefficients of figures 1, 2 and 3, thus obtaining by simple calculations results that are quite sufficiently accurate.

807. We will apply this method to a case which frequently presents itself; that of a horizontal cast iron pipe containing steam at 212° F. and with a surrounding temperature of 59°.

For $r = 2''$ $M = 153 \times .688 \times 1.52 \times 1 + 153 \times .58 \times 1.56 = 298$
$= 4''$ $M =$ " " " $+$ " $\times .50 \times$ " $= 279$
$= 6''$ $M =$ " " " $+$ " $\times .47 \times$ " $= 261$

The results are in B. T. U. per square foot of surface per hour. The weights of steam condensed by direct experiment are a little greater, probably on account of water mechanically entrained by the steam.

809. For a horizontal pipe of sheet iron 10 inches in diameter containing air at 302° F., the exterior air being at 59°, we would have $M = 243 \times .567 \times 1.88 \times 1 + 243 \times .48 \times 1.73 = 462$ B. T. U. per hour per square foot.†

Emission of Heat from Pipes to Air.

821. *Emission of heat from the surface of a pipe to the air traversing the pipe. The surface being maintained at a constant temperature.*

Let us consider a metal pipe, the surface of which is main-

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*In French units.

†It will be noticed that in these examples the second coefficient by which K is multiplied in order to obtain R is unity. This is because the temperature of the surrounding objects is 59° F. See figure 3, page 21.

To sum up we have for our working formula,

$M = R + A = (T - t) \times K \times C \times C' + (T - t') \times K' \times C''$

In which,

M = B. T. U. per square foot per hour.

R = " " " " due radiation.

A = " " " " due air contact.

T = temperature of the body emitting heat in F °.

tained at a constant temperature, and through which passes a current of air; and let us suppose that all the elementary veins have sensibly the same velocity or that a thin slice of air taken perpendicularly to the axis of the pipe at the entrance preserves its form while it traverses the pipe.

During its passage the circumference of the section will be at the temperature of the pipe, and the heat will propagate itself from the circumference towards the centre. After a certain time the whole section will have attained sensibly the temperature of the pipe; if at this moment it has not reached the end of the pipe, the rest of its passage will evidently be without influence, if at its exit from the pipe the heat has not had time to reach the centre of the section the mean temperature of the section will be the higher the longer it has been in the pipe. The temperature of the escaping air will depend then on its velocity, and on the length of the pipe.

We have supposed the pipe to be circular and the slice of air to be always limited by two plans, but all that we have said is equally true for a pipe of any form whatever, and in spite of the difference in velocity of the elementary veins which always takes place; except that the time necessary for the centre of the vein to take the temperature of the circumference augments with the difference of velocity.

We may add that when the pipe is horizontal or more or less inclined, the propagation of the heat depends not only on the transmission through the air, but also on the movement of the air due to its being heated.

It is easy to see from these considerations how complicated are the phenomena which take place during the heating of air while it traverses a pipe maintained at a constant temperature, we may however deduce certain general principles from the preceding reasoning, which will be useful under certain conditions.

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t =temperature of objects to which radiation takes place in F°.
t' = " of surrounding air in F°
For value of K see 794.
" " K' see 798-802.
" " C see Figure 2, page 21.
" " C' see Figure 3, " "
" C'' see Figure 1, " ".

1st. When air traverses a tube maintained at a constant temperature greater than that of the air and supposing that the velocity of the air, at first very small, increases as it progresses through the tube, the air will emerge at the temperature of the tube up to a certain limit of velocity, depending on the perimeter of the tube, on the shape of its section and the inequality of the velocities of the different elementary veins. This velocity will increase in proportion as the section of the pipe diminishes. It is impossible to foresee whether, under the same conditions, this velocity would be greater in a vertical pipe than in a horizontal one, because in the first case the increments of velocity resulting from heating against the walls brings out the air from the centre, while in the second case the layers of air in contact with the lower surface are constantly displaced, circumstances which both tend to distribute the heat.

2nd. When the limit of velocity which I have just mentioned has been reached, the air escapes at a decreasing temperature because in each section the temperature is decreasing from the circumference to the centre, and the greater the velocity of the air the more is this the case. But the quantity of heat carried off by the air increases with its velocity, this fact is thoroughly proved by experiment and is easily explained by admitting that the sum of the quantities of heat diffused through each section increases very rapidly with time, for the number of sections passing in unity of time being proportional to the velocity, and the time of passage of each section being inversely proportional to the velocity, it follows that the quantity of heat carried off by the air will increase with the velocity provided that the quantity of heat which diffuses itself through a section increases very rapidly with the time.

822. In practice we may admit as a sufficiently close approximation that the quantity of heat emitted by the pipe is sensibly equal to that which it would emit in the open air by air contact to the surrounding air at a temperature the mean of the observed temperatures of the air at entering the pipe and at leaving it.

I have verified this principle by means of a cylindrical vessel 16 inches high, and 8 inches in diameter, pierced at the centre by a tube 4 inches in diameter with its surfaces entirely covered by paper. By observing the cooling when the orifice of the tube was open and then when closed, I have found that in the last case the loss of heat was very nearly equal to half of that of the central tube when surrounded by free air.

823. *Emission of heat to air traversing a conduit enclosing a pipe maintained at a constant temperature.*

This case is very similar to the preceding one, except that the diffusion of the heat takes place more rapidly, because the concentric layers of air undergo a continual increase of surface as they recede from the surface of the pipe, and at the same time the interior surface of the conduit, heated by radiation, heats the layers of air from the opposite direction. Here, as in the preceding case, there is a limiting velocity, below which the heating of the air is complete, and beyond which the temperature of the air diminishes, although the quantity of heat carried away increases with the velocity.

824. For this case we may estimate the quantity of heat emitted to be approximately equal to that which the pipe would emit in the open air by radiation and air contact, the temperature of the surroundings being taken as the mean of the observed temperatures of the air at entering the conduit and at leaving it.

CHAPTER II

Transmission of Heat through Solid Bodies.

When a solid body is limited by two parallel surfaces, maintained at temperatures constant but different, it is traversed by a constant flow of heat proportional to the distance between these two surfaces. This law may be deduced from the very nature itself of the movement of heat. Consider a homogeneous plate, of thickness e, of unit superficial area, and of which the surfaces are maintained at the constant temperatures t and t', imagine the thickness of the plate to be divided into a very great number of extremely thin layers. The entire thickness of the plate being obviously traversed simultaneously by a quantity of heat equal to that which traverses any part whatsoever of its thickness, an equal quantity of heat must pass simultaneously through each of the elementary layers in question, then, since for any particular body the quantity of heat transmitted can only depend on the thickness, and on the difference of temperature, and since the thicknesses are the same, it follows necessarily that the differences of temperature of the surfaces of the elementary layers are the same, and in consequence, that throughout the thickness of the plate the temperature varies uniformly from t to t'. As the quantity of heat which traverses any layer is the same as that which traverses any number whatsoever of layers, and since the difference of temperature of the outer surfaces is proportional to the number of layers, and as the thickness is also proportional to the number of layers, the equality in question can only exist as long as the flow of heat is proportional to the total thickness, and we have

$$M = \frac{C(t-t')}{e}$$

In this expression M represents the quantity of heat transmitted by unit surface in unit time, t and t' the temperatures of the two surfaces, e the thickness of the plate and C the *conductiv-*

ity of the material, that is to say the value of M for $t-t'=1$ and $e=1$.

This formula has been verified by experiment.

We will first examine the conductivity of bodies which transmit heat well, that is to say the metals, and then the conductivity of bodies which transmit heat poorly.

CONDUCTIVITY OF METALS

827. When one end of a bar of metal is maintained at a constant temperature, heat is transmitted along the bar and is dissipated from its surface. If we suppose the bar to be so long that the heat does not reach its farther extremity, and its section to be so small that all the points of the same section have sensibly the same temperature, we may readily find by calculation, for the excess of temperature y of any section above that of the air, at a distance x from the extremity, the relation,

$$y=Ae^{-x\sqrt{\frac{Ph}{Cs}}}$$

in which A represents the constant excess of temperature of the heated extremity over that of the air, S the section of the bar, P its circumference, h its coefficient of cooling, and C the conductivity of the bar.

828. In 1816 M. Biot verified the truth of this formula by numerous experiments (Traité de Physique, 1816). Later in 1836 M. Despretz made further experiments which confirmed those of M. Biot and which permitted him to determine the relative conductivity of the metals, given in the following table: *

Silver	1000	Iron	119
Copper	736	Steel	116
Gold	532	Lead	85
Tin	145	Plantinum	84

829. These numbers cannot however be considered very exact since to begin with, Newton's Law on which the formula (827) depends, departs too far from the truth when the excesses of temperature are considerable, and further because in measuring the temperatures of the various sections of the bar holes were

* The table given here is from more recent experiments of Frantz and Wiedermann in which the errors due to boring holes in the bars were avoided by the use of thermopiles.

bored for the insertion of the thermometers, thus producing points of reduced sectional area, which must have had some influence on the results.

830. Since the numbers found by M. Despretz were relative only, they could not serve for any applied calculation so long as the absolute conductivity of no one of the metals was known. In 1841 I took up the question and in order to determine the conductivity in heat units I made a great number of experiments of which a detailed description will be found at the end of this work; I shall limit myself here to a brief description of the apparatus employed and to the setting forth of the results.

A cylindrical vessel full of water and surrounded by non-conducting material was provided with a bottom formed by a disc of metal of which the circumference was separated from the walls of the vessel by a ring of cork. The lower surface of the disc was heated by steam, and the heating of the water contained in the vessel was observed. The water was kept in constant motion by an agitator. If we admit that the amount of heat traversing the disc is proportional to the difference of temperature of the two surfaces, and remembering that this amount of heat is proportional to the rate of cooling (776) we have $dT=aTd\,t$; and m log. $T=C-a\ t$, m being the modulus of the table of logarithms, 2.3025 and T the difference of temperature after the time t.

If we designate the temperature corresponding to $t=o$ by A we find $C=m$ log. A, since in this case $T=A$, and the formula gives $a=\frac{m}{t}(\log.\ A-\log.T)$

The logarithms are those of the tables and a is the cooling which would take place in one second for a difference of temperature of one degree. Two observations gave a value of a, and the identity of these values deduced from different pairs of observations proved the truth of the hypothesis on which the formula was based. These experiments repeated with discs of lead, zinc, tin, sheet iron, and cast iron, gave the same results. But what at first astonished me very greatly was the fact that the values of a were sensibly the same for these different metals, no matter what their thickness was, although it varied from one to twenty millimeters. In all the experiments, I noticed that the speed of rotation of the agitator had a very perceptible influence; the value of a increased or diminished notably with this speed. When we consider that the steam in condensing must cover the lower surface of the disc with a layer of almost motionless water it is very probable that in these experiments this surface was not at the temperature of the steam, and likewise that the upper surface was not at the temperature indicated by the thermometer. The heat was really traversing a sheet of metal, comprised between two sheets of water, one of which was practically motionless and the other was only slowly changed; and since the conductivity of water is very low compared to that of the metals, the influence of the conductivity of the metals disappeared.

831. To verify this conjecture I abandoned the heating by steam. I filled the upper vessel with water at $O° C$ and I immersed the disc which formed its bottom to a depth of several millimeters in a vessel filled with water at ordinary temperature. The interior agitator was provided with brushes which grazed the surface of the disc and the water in contact with the other surface was renewed by cords stretched in a frame to which a rapid reciprocating motion was imparted.

With this arrangement the heating of the water in the vessel was very slow and the water in contact with the disc could be changed with great rapidity.

With the discs of lead from one to twenty-five millimeters thick, the values of a varied from .00060 to .00025. The other metals gave similar results.

From this I concluded that, by greatly increasing the rate of renewal of the waters bathing the two faces of the disc, and by employing thick discs of the metals with the lower conductivities, coefficients would be obtained that would be inversely proportional to the thicknesses.

832. I devised for this purpose a new apparatus, in which the interior agitator was driven by gearing; the external agitator was also geared and consisted of a horizontal wheel, mounted eccentrically to the vessel and having spokes formed by tightly stretched cords, which in their motion rubbed against the outer surface of the disc.

Figure 165 is a vertical section of this last apparatus, figure

166 a horizontal projection, and figure 167 a section on a larger scale of the lower part of the interior vessel, $A\ B\ C\ D$ is a vessel of tin closed at its lower end by the disc of metal E, of which the manner of attachment is shown by figure 167. This vessel has within it a copper tube bearing paddles at different heights and having at its lower end a horse hair brush. This tube is guided by two rings secured to it by the rods $I I$ and $I' I'$ and it bears at its upper end a pinion driven by means of the gear and crank M'.

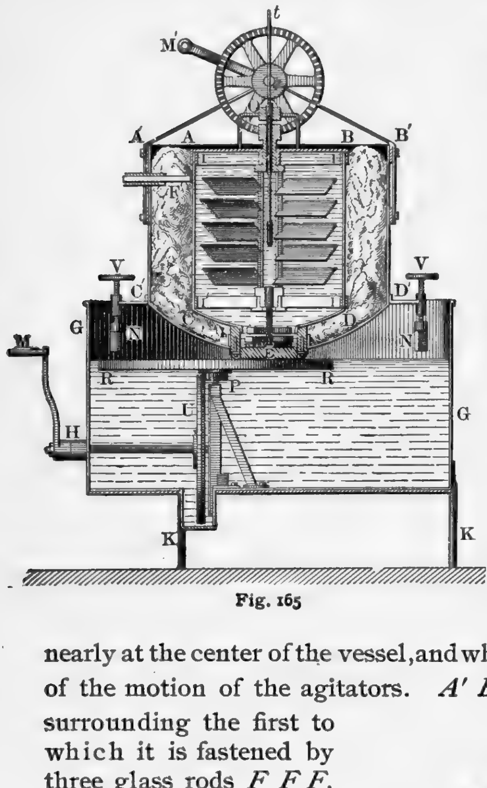
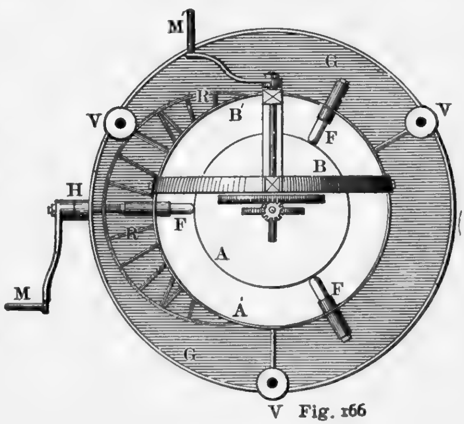


Fig. 165

The vessel is closed by a tight cover through which the central copper tube projects. This cover supports a ring O, one centimeter above the top of the tube, in which is placed a pierced stopper through which passes the stem of the thermometer, whose reservoir is nearly at the center of the vessel, and which remains fixed regardless of the motion of the agitators. $A'\ B'\ C'\ D'$ is a second vessel surrounding the first to which it is fastened by three glass rods $F\ F\ F$, it is filled with cotton wool and its three feet are provided with screws engaging in the supports $N\ N$ soldered to the lower vessel $G\ G$. The vessel $A'\ B'\ C'\ D'$ supports the crank and gear that drives the pinion of the central tube. Finally the



V Fig. 166

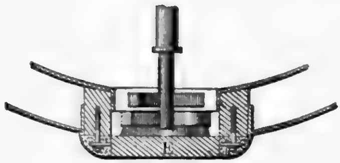


Fig. 167

vessel G G contains a horizontal wheel R R having spokes formed of cords which rub as the wheel revolves against the lower surface of the disc E. This wheel is driven by the pinion P, the gear U and the crank M of which the shaft passes through the stuffing box H.

By means of this apparatus I was able to renew 1600 times per minute the water in contact with the surfaces of the metallic disc.

With water at very nearly 24° C in the open vessel, and at the atmospheric temperature in the inner vessel, and employing discs of lead of twenty and fifteen millimeters in thickness, the duration of equal amounts of heating of the water in the interior vase was 500 seconds for the first disc and 380 for the second, this last figure only differs by five seconds from three-quarters of the first.

We may therefore consider the law of thicknesses as having been proven by direct experiment.

In these experiments the mean temperature of the outer bath was 24.04° C and only differed from the extreme temperatures by a small fraction of a degree. The excesses of temperature at the beginning and the end of the experiment were 8.91° C and 9.55° C.

Then the quantity of heat transmitted through the 20 mm. disc was .000294 per minute; the weight of water enclosed in the vessel increased by the weight of the vessel multiplied by its specific heat being 3.287 kilograms, the quantity of heat which would be transmitted through the disc for a difference of 1° C would equal, $.000294 \times 3.287 = .000966$ and as the surface of the disc was .005026 square meters the quantity which under the same circumstances would be transmitted per square meter would equal, $.000966 \times \frac{1}{.005026} = 0.192$ and for a disc one meter thick, and during one hour would equal $.192 \times .02 \times 3600 = 13.83$* and this figure is the conductivity of the metal.

833. Then if we admit the correctness of the relative con-

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*113 B. T. U. per hour per square foot per 1° F. per 1 inch thickness.

following figures for the quantity of heat in British thermal units, which would be transmitted in an hour through plates with a superficial area of one square foot, a thickness of one inch, and of which the surfaces are maintained at constant temperatures differing by one degree Fahrenheit.

Silver	1330	Iron	158
Copper	980	Steel	154
Gold	706	Lead	113
Tin	193	Platinum . .	112

But these conductivities have been obtained under special circumstances which are never met with in practice.

According to some old experiments of Clément, a sheet of copper 10.8 square feet in area, and one-tenth of an inch in thickness, bathed by steam on one side and water at 82° on the other, condensed 220.5 pounds per hour for a temperature difference of 130 degrees, which is equivalent to 1.7 pounds for a difference of one degree Fahrenheit.

According to the more recent experiments of Thomas & Laurens, with a single copper tube of small diameter, there was evaporated 81.8 pounds of water per hour, per square foot, for a temperature difference of 81°, which makes one pound for a difference of 1° F.

The figure obtained by Thomas & Laurens is much greater then Cléments, for the surface of transmission being a tube of small diameter, the air was completely expelled, a circumstance which greatly augments the amount of steam condensed.

It is evident that even under the most favorable circumstances, the figure obtained for the transmission of heat through copper, when the liquid wetting the surfaces is not renewed, is much less than that resulting from the experiments we have been considering. This is on account of the sensibly motionless layer of water which covers at least one of the surfaces.

834. Thus, although the laws admitted by physicists for the transmission of heat through plates may be exact, these laws are not applicable to the transmission of heat from one liquid to anductivities of the metals found by M. Despretz† we obtain the

†See foot note to paragraph 829. The figures given here are based on Pèclet's experiment with lead and the relative values of Franz and Wiedermann.

other through a sheet of metal; and we may admit that, within the limit of thicknesses generally employed, the material and thickness of the metal are without sensible effect; but if in certain cases there should be a great advantage in increasing the rate of this transmission, even at the expense of doing work for this purpose, it could be effected by a stirring which would very rapidly renew the layers of liquid in contact with the plate.

All of the preceding remarks suppose both surfaces of the plates to be bathed by liquids, and should therefore be only applied to heating of liquids by liquids, or by steam; for steam in condensing on the surfaces of the plates wets them and all takes place as if the heating were done by a liquid. But when liquids are heated by gases, and when gases are heated by other gases is it still the same? It is this which we will examine next.

835. Consider first the heating of liquids by gases, this is for example, the case with steam boilers, at least for that part of a boiler which does not receive the radiation from the grate. I have made no direct experiments on this subject, but the results of practice leave no room for doubt that if the nature and thickness of the metal have any influence it is only very small; for it has been recognized for a long time that boilers of cast iron, of copper, and of wrought iron, of the same dimensions but of widely differing thicknesses, give sensibly the same results under the same circumstances. It is a fact upon which all engineers agree. One may easily account for it: when the thickness of metal increases or its conductivity decreases, the temperature of its outer surface rises; a well proven fact since in cast iron boilers the exterior often becomes red, and as to wrought iron boilers, the change of shape which they experience from the heat increases with their thickness. Now since the quantity of heat transmitted increases as the exterior temperature increases, it is easy to see that the effect of the nature and thickness of the metal is but slight.

This has been proven further by recent experiments of M. Boutigny; who evaporated water in silver capsules of the same form and exterior dimensions but of very different thicknesses; the quantities evaporated under the same conditions and in the same time were precisely the same.

836. In regard to the transmission of heat from one gas to another through a plate of metal, as for equal volume gases have much less capacity for heat than liquids and as their conductivity is very feeble, we may regard the influence of the nature and thickness of the plate as absolutely nonexistent, since the quantity of heat which the plate can transmit, even under the most unfavorable conditions, is incomparably greater than that which actually traverses it, and consequently in no case can the thickness of the metal delay the transmission. The quantity of heat which traverses the plate is determined solely by the difference of temperatures of the two gases, the absorbing and radiating powers of the two surfaces of the plate, and above all by the movements of the sheets of gas in contact with these surfaces.

Thus we see that in every case the rapid renewal of the layers of gas or liquid, which bathe the surfaces of the metal plate, has a very great influence on the transmission of heat, but that this circumstance is of much greater importance with gases than with liquids.

837. One should then in designs seek the disposition most favorable to this renewal, taking advantage of the motions which the fluids must have in order to pass through the apparatus, and those resulting from heating and cooling. But with gases, one may also artificially produce motions throughout their masses which would cause rapid renewals of the layers in contact with the metallic surfaces, either in some direct way requiring only a small amount of power, or by employing a part of the force resulting from the passage of the gas.

838. Consider, for example, air heated to an extremely high temperature, escaping through a horizontal cylindrical conduit surrounded by water which it is intended to heat. The layers of air in contact with the metal cool very quickly; but as all the little elementary veins possess motion only in the direction of the axis of the conduit, the layers will change place but slowly, for the sole cause of change lies in the increase of density resulting from cooling; it only exists for the upper half of the conduit, and it only operates slowly. This same state of affairs will continue no matter what the direction of the conduit. We may imagine according to this, that if the area of the conduit were

very great, and the velocity of the air at its exit very high, that the greater part of the central veins would not come into contact with the wall of the conduit, and would preserve their original temperature. But if one provided the conduit with fan wheels mounted on a shaft driven by power, the central veins would be thrown out against the metal of the conduit and one would thus obtain much greater cooling of the gas. The movement of the gas from the centre to the circumference could even be produced by the passage of the gas itself. It would suffice to place in the conduit a number of wheels with vanes inclined as are the vanes of a windmill; these wheels on which the movement of translation of the gas would impress a certain velocity of rotation, would evidently produce the same effect as wheels with blades set in the plane of the axis of rotation.

839. The transmission of heat may be increased by still another proceeding which is in some circumstances very efficacious.

We have seen that in the transmission of heat through a metal plate, it was necessary to distinguish between the absorption by one face, the emission by the other and the transmission through the metal; and we know that under ordinary circumstances, the quantity of heat that the plate can transmit is much greater than that which it can absorb or emit. It results from this that if we use plates provided with projecting rods that dip into the two liquids or gases, the one of which is to heat the other, we increase the extent of the surfaces in contact with the two fluids, and in consequence the effect produced; so much the more since the veins of fluid in contact with the rods will be constantly renewed by the motion of translation of the fluids.

We may take for an illustration a horizontal conduit traversed by highly heated air intended to heat the air, moving in an opposite direction, in a surrounding conduit. If the surface of the inner conduit is provided with rods projecting inside and out, and if they are not arranged in parallel rows, the inner portion of the bars will absorb heat throughout their length and this heat will be dissipated by the exterior portions; the current of hot air will be cooled uniformly throughout its section and the heat will be transmitted to all points of the section of the exterior current of air. This arrangement may be useful, especially when it is important to effectuate the transfer of heat in a small space; but it often has drawbacks, either on account of difficulty in construction, or in cleaning the surfaces of absorption and transmission.

840. Most important of all, whenever it is a question of transferring the heat of one body in motion to another, is it that the latter body moves in a direction opposite to that of the first, for as the hot body progresses it encounters the body, to which it is to transfer its heat, at a lower temperature, and the transmission continues, which would not be the case if the two bodies were moving in the same direction. Consider, for example, two concentric tubes, the inner tube conveying hot air or water, and the interval between the two tubes, which we will assume equal in sectional area to the inner tube, conveying cold air or water in the opposite direction. If the tubes are sufficiently long and the motion of the fluid slow enough, it is evident that there will be a complete exchange of temperature before the exit of the air, or water, whilst if the two fluids travelled in the same direction, as one cooled and the other heated, their temperatures would constantly approach and would finally become the same, and from this point on all transmission of heat would cease.

CONDUCTIVITY OF POOR CONDUCTORS OF HEAT.

841. The case of materials which are poor conductors of heat is different from that of the metals, in nearly every case they propagate all the heat which they are really able to transmit and it is very important to know their conductive power.

M. Despretz is the single physicist who has occupied himself with the conductivity of a few of these bodies. Experiments on the propagation of heat through bars of marble, porcelain and brick gave 23.6, 12.2, and 11.4 as the relative values of the conductivities of the three materials. But the manner of making these experiments presents not only the causes of error already explained (829) in speaking of the conductivity of metals, but also that resulting from the hypothesis of uniformity of temperature at all points of the same section, an hypothesis the more untrue the less the conductivity of the material under experiment. Even supposing these experiments to be perfectly exact, the results are only relative and therefore cannot be used in practical applications.

842. In the second edition of this work I have given the results of some experiments on the conductivities of the materials under consideration, but the methods then employed were not exact enough to give in every case sufficiently accurate results. I have taken up these researches again using varied and more precise methods; the details of which will be found in an appendix to this edition, I shall limit myself here to a review of the methods used, and a statement of the results obtained.

843. In the first method which I have employed, the material under experiment was enclosed between two spheres of thin copper; the inner sphere was filled with warm water constantly stirred, and the outer sphere was submerged in a bath, of considerable size, of water at the ordinary temperature; this latter was constantly stirred in the immediate vicinity of the sphere. It can be shown by calculation that the cooling of the warm water follows Newton's law, provided that certain relations between the temperatures of different points of the spherical envelope hold true at the beginning of the experiment, and these relations are satisfied by bodies which are not too poor conductors of heat. The coefficient of conductive power may then easily be deduced from the rate of cooling. For quartz sand, mahogany sawdust and starch paste, the rate of cooling followed exactly the law indicated above, and I was able to obtain the conductivity of these materials. But for cotton and powdered charcoal the cooling followed a more rapid law and no definite conclusions could be drawn from the experiments except that in the case of cotton the rate of cooling under the same circumstances was sensibly the same for densities varying from .0077 to .076, and I arrived at the conclusion that the conductivity of this material was independent of its density and in consequence that the conductivity of the fibre composing it must be equal to that of motionless air.

844. Figure 168 represents a vertical section of the apparatus, *A B C D* is a copper frame placed in a leadplated iron vessel filled with water at ordinary temperature. The lower member *B C* of the frame is provided with three toothed wheels *E F* and *G* (fig 169).

The wheel E is driven by the vertical shaft HI provided with a steadiment at L and a crank K at its upper end. The wheel G is loose on the fixed shaft M, in which is supported the stem N soldered to the surface of the outer sphere, which it is intended to support.

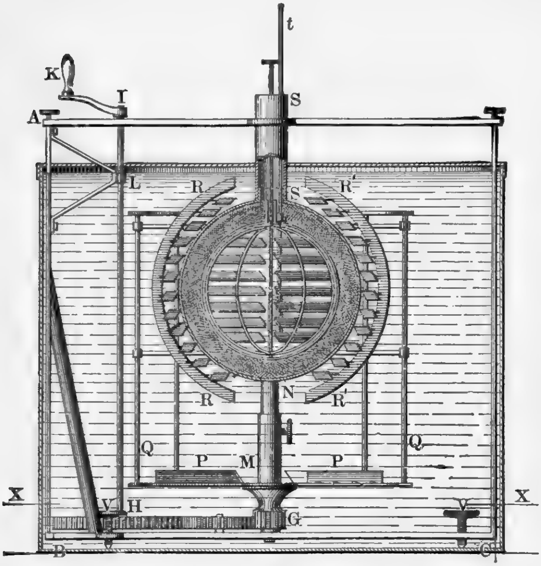

Fig. 168

The wheel G carries a horizontal ring with eight spokes, each provided with a copper plate inclined at 45°; at its circumference are eight vertical stems Q Q, bound together at the top by another horizontal ring; each of these rods holds arcs of circles R R, R' R', provided with a large number of small inclined copper plates, with edges almost touching the outer sphere. S S is a copper cylinder fastened at the upper part of the outer sphere. It covers three stuffing boxes communicating with the inner sphere; through one of these passes a thermometer, through another the stem of an agitator, and the third, ordinarily closed, may receive the stopper carrying the tubes designed to refill the inner sphere when the level of the water has sunk.

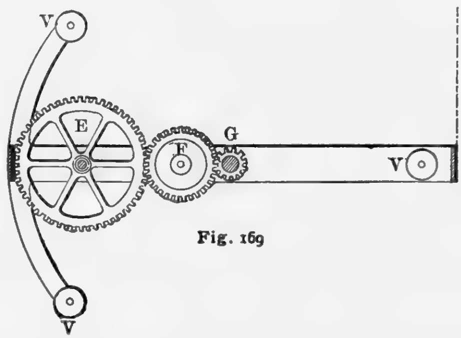

Fig. 169

The outer surface of the small sphere and the inner surface of the large sphere are covered with lamp black. The outer

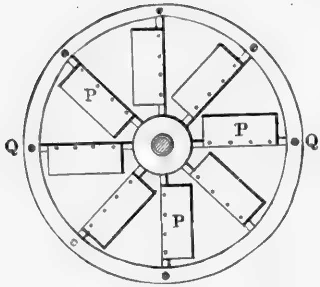

Fig. 170

sphere is in halves which fit into one another, the joint being made water tight with wax. Thermometers, not shown in the figures, give the temperature of the water in the outer vessel. Throughout an experiment the water in the inner sphere was agitated by an apparatus similar to that employed in the experiments on cooling in air (782) and the water in the outer vessel was stirred by turning the crank *K*.

The rate of cooling was measured in the same way as in the experiments on cooling in air, and with the same corrections in regard to the water introduced into the vessel before each observation in order to maintain it full.

845. In the second method I have used a hollow cylinder of the material of which I wished to determine the conductivity; its interior was heated by steam and its exterior exposed to the air in the constant temperature chamber used in the experiments on cooling in air. When the régime is established, the quantity of heat passing through the walls of the cylinder is evidently equal to that escaping from its surface. Now there exists a very simple relation between the inner and outer radii of the cylinder, the temperatures of the steam, of the outer surface of the cylinder and of the surrounding air, the rate of cooling of the outer surface, and the conductivity of the material forming the cylinder. All these quantities can be easily measured, except the temperature of the surface of the cylinder. We shall show presently how this has been determined.

846. Figure 171 shows the general arrangement of the apparatus. For powdered substances I used a cylinder of tin *a b c d* eight inches in height, and of different diameters, covered with paper; it was surmounted by a tube *e f* closed by a stopper at its upper end through which passed the stem of a thermometer with its 212° mark just above the top of the stopper; this tube was provided with an outlet *f g* communicating with a vessel producing steam. Attached to the bottom of the cylinder was a tube *h i k*,

bent at *i*, serving as a drain for the water of condensation and any excess of steam. Three quarters of an inch below the cylinder *a b c d*, the tube *h i* was provided with three projecting pieces of iron

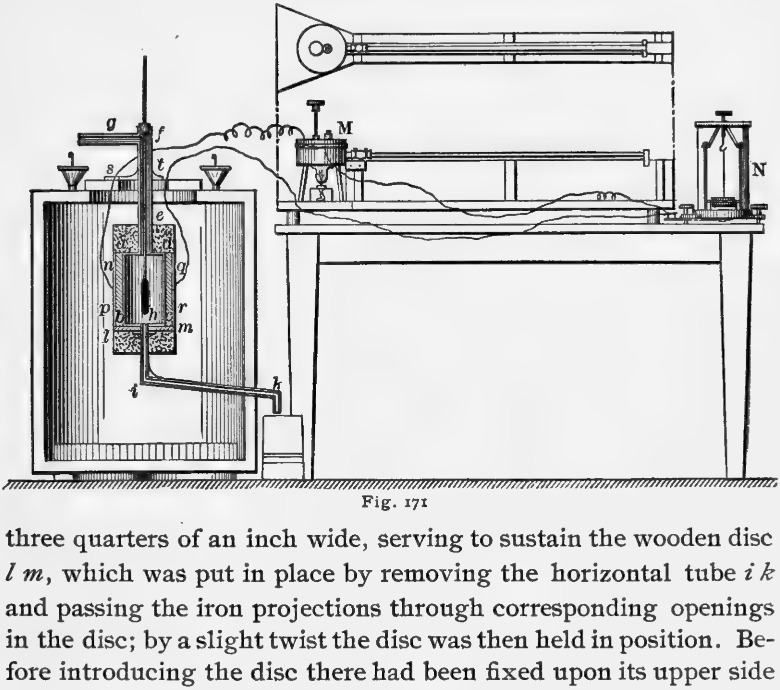

Fig. 171

three quarters of an inch wide, serving to sustain the wooden disc *l m*, which was put in place by removing the horizontal tube *i k* and passing the iron projections through corresponding openings in the disc; by a slight twist the disc was then held in position. Before introducing the disc there had been fixed upon its upper side a cylinder *n p q r* of very thin glass, open at both ends, and of the same diameter as the disc, and maintained in position by means of a band of paper glued to both the glass and wood. The whole surface of the glass cylinder was covered with paper and the sheet of paper projected at both ends for nearly four inches. The material to be experimented on was placed between the two cylinders *a b c d* and *n p q r*, and the paper cylinders forming prolongations of the glass cylinder were filled with carded cotton. The apparatus which we have just described was suspended within the constant temperature chamber, used in the experiments on cooling, by means of the supports *s t*. Steam was allowed to flow into the tin cylinder *a b c d*, often for several hours, so as to be well assured that a constant régime had been established.

847. The temperature of the outer surface of the cylinder

was obtained in the following manner; a very thin band of iron four-tenths of an inch wide, and six and a half feet long, was soldered at each end to bands of copper of the same dimensions; one of the joints and the adjacent portions of the bands were bound to the cylinder of glass, the other joint was secured in like manner to a cylindrical vessel *M* containing water, an agitator and thermometer and provided with a lamp by which the water could be readily heated, finally the two free ends of the copper bands were connected through a very sensitive galvanometer N. When it was desired to measure the temperature of the surface of the cylinder, the circuit was closed, and the water in the vessel *M* heated until the needle of the galvanometer returned to zero; at this instant both joints between the iron and copper bands were at the same temperature and consequently that of the surface of the cylinder was the same as that of the water in the vessel *M*. To fasten the joints against the surfaces of the two cylinders I used a band of cotton, three quarters of an inch wide, which enveloped the metal band and pressed it against nearly the whole circumference of the cylinder; the band was held clasped by a buckle, and the free ends of the metal emerged from slits in the cotton. The thermometer serving to indicate the temperature of the water in the vessel whose surface was in contact with the second junction of the bands, was placed horizontally that it might be the more easily read; its stem being protected by a vertical board beneath it; one could easily estimate one-hundreth of a degree. The vessel was heated by an alcohol lamp. The galvanometer made by M. Ruhmkorff was sensitive enough to indicate one-fortieth of a Fahrenheit degree difference in the temperatures of the two junctions.

848. The cylinder of glass had no influence on the results, on account of its thinness and the high conductivity of the vessel. I also used a paper envelope glued to three tin cylinders four-tenths of an inch wide of the same diameter and with the same axis, held in position by two narrow strips of tin (Fig. 172). The strips of tin made it possible to fasten closely the metallic band serving to measure the temperature of the surface of the cylinder. This meththod gave the same results as the glass cylinder.

Fig. 172

849. For solid bodies such as stone and marble I used hollow cylinders painted inside with oil, and covered on the outside with paper; more often to be the better assured that water could not penetrate the material the outer surface was covered with tin foil. The cylinders were closed at each end by a sheet of rubber and then by a disc of wood. In the case of the wooden cylinders, the steam entered at top, and escaped at bottom as with the tin ones. They were supported from the lower end, and insulated at both ends by means of paper cylinders filled with cotton. (Fig. 173). For wood I used the same arrangement when determining the conductivity perpendicular to the fibres; but to measure it parallel with them I employed portions of cylinders having surfaces perpendicular to the fibres, these were strongly compressed against a tin cylinder covered with paper, having an outer radius equal to the inner radius of the wooden cylinder.

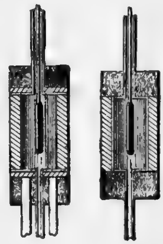

Fig. 173 Fig. 174

850. Papers and cloths were rolled around a tin cylinder, always covered with paper, and they were held in position by a cylinder of strong paper having a height double that of the tin cylinder. This paper cylinder was held by the metallic band (Fig. 174).

851. The formula which gives the conductivity is as follows:

$$C = \frac{Q\,R'\,m\,(t''-t''')\,(\log.\,R' - \log.\,R)}{t'-t''}$$

In this formula C is the conductivity of the material, R, R' the radii of the inner and outer cylinders; $m = 2.3025$; $t,'$ $t,''$ $t,'''$ the temperature of the steam, of the outer surface of the envelope and of the air; Q represents the coefficient of emission of the heat from the surface, and equals $K + K'$ (791), the values of K and K' having been corrected by the coefficients taken from the curves of figure 1, 2 and 3.

852. Finally in the last method I employed vertical rectangular plates, insulated around their perimeter; one of the surfaces was heated by steam, and the other exposed to the free air of a constant temperature chamber. A formula even more simple than that of the cylinders permitted the calculation of the con-

ductivity from the same elements; but I have employed a different and much more exact method of measuring the temperature of the exposed surface. Opposite the heated plate was placed a vessel of the same form filled with water; the opposing surfaces of the two vessels were covered with paper, and the poles of a very sensitive thermopile, connected with a galvanometer, were placed exactly equidistant from both; it is evident that when the needle of the galvanometer was at zero, the temperature of the exposed service of the plate was the same as that of the water in the vessel.

853. Figure 175 is a plan of the apparatus, figures 176 and 177 elevations of the two longer sides, figure 178 a section perpendicular to the elevations. In all these figures the same letters indicate the same objects. *A B C D* figure 175 is a rectangular closed tank of sheet lead full of water; it is surrounded by a wooden box *X X X X*; the bottoms and ends of these two vessels are separated by spaces of two and a half inches.

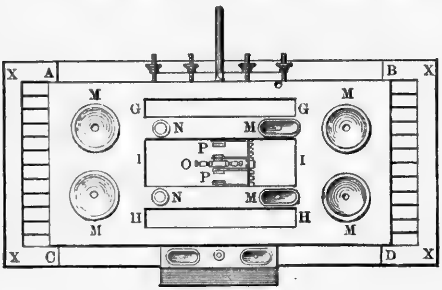

Fig. 175

The long sides of the tank are only partly covered with wood. The spaces *A X X C* and *B X X D* between the ends of the tank and the box are provided with a great number of metal strips soldered vertically on the tank, the object of this is to impart to the air passing down the spaces *A X X C* and *B X X D* the temperature of the water in the tank. *G G* and *H H* are two vertical rectangular conduits passing entirely through the tank and communicating

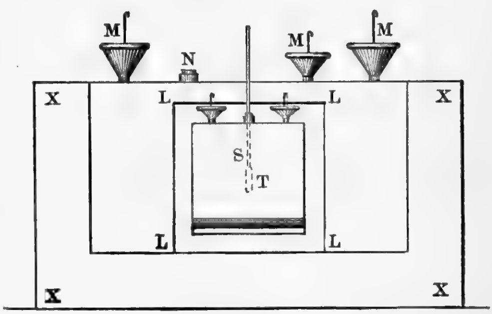

Fig. 176

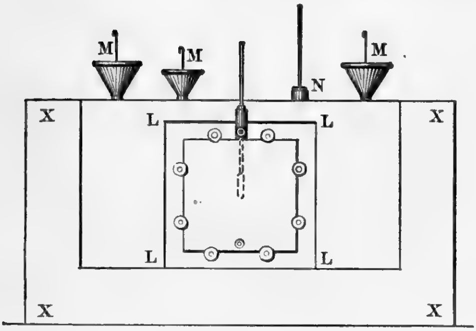

Fig. 177

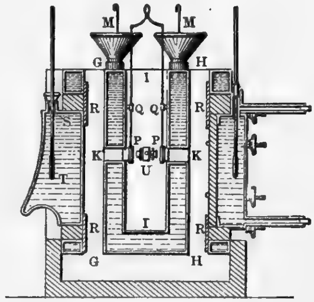

Fig. 178

by the space beneath it with the openings *A X X C* and *B X X D*. *I I* is an opening in the tank but it does not penetrate completely through it. *K K* (fig 178) are two horizontal tubes with the same axis and of the same diameter, open at both ends, *L L L L* are openings eight inches square formed in the long sides of the tank, which pierce from the outside into the conduits *G G*, *H H*. These conduits, cylinders and openings are surrounded by water, *M M M M* are funnels surmounting openings through which pass agitators. *N N* are openings for thermometers. *O* is a thermopile in the enclosure *I I*, opposite the common axis of the two tubes *K K* and equidistant from their inner ends; its poles are connected with a very sensitive galvanometer not shown in the figures. *P P* are substantial double screens, capable of movement about the axis *Q Q*, and intended to intercept the rays of heat reaching the thermopile through the tubes *K K*. The openings *L L L L* receive the bodies whose surfaces act upon the thermopile; but as these surfaces must always be at the same distance from the thermopile, the inner edges of the openings *L L L L* are provided with four stops *R R R R* against which the bodies are supported. Figure 179, representing one side of the tank when the opening *L L L L* is empty, shows the arrangement of these stops.

854. One of the openings *L L L L* is always occupied by a copper vessel *S T* (fig 178) full of water, and provided with two agitators and a very sensitive thermometer; a part of its lower surface is so arranged as to be easily heated by an alcohol lamp. This vessel is surrounded by a frame of fir wood, which separates it

from the perimeter of the opening, so as to avoid heating the water in the tank, it is held in place by small wooden wedges.

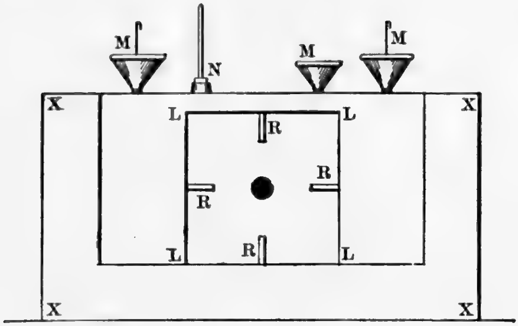

Fig. 179

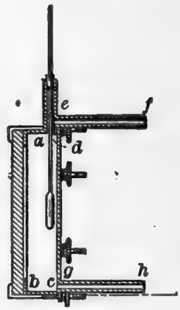

Fig. 180

855. In the other opening are placed the plates of which the the conductivity is to be measured; these rest against the stops *R R R R* and their outer surface is heated by steam. Their construction is suitably varied for solid or powdered material. In figure 178 we have assumed the material under test to be solid; figure 180 shows the construction on a larger scale; *a b c d* is a rectangular box of copper having one face provided with a large opening shown in figure 181 and 182, the first of which is an eleva-

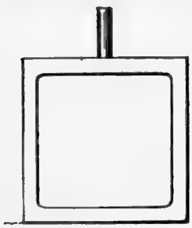

Fig. 181

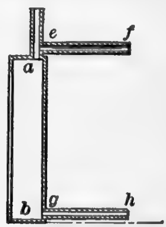

Fig. 182

tion of the face *a b* and the second a section perpendicular to this face. Steam is admitted by the tube *e f*, and the water of condensation and along with it any excess steam escapes by the tube *g h*; a thin narrow rubber gasket is laid around the opening in the face *a b*, and against this the plate is held by copper rods, hooked at one end and provided with thumb screws at the other. The vessel is fitted with a thermometer for ascertaining the temperature of the steam, and is surrounded by a wooden frame like that of the water vessel in the opposite opening, it is secured in the same way by wooden wedges.

Fig. 183

Figure 183 shows the construction for powdered material, the steam box is solid and surrounded by a wooden frame to insulate it from the tank, and the front of the frame is closed by a thin sheet, either of glass or tin plate, covered on both sides with paper, the outer paper serving to fasten the sheet in place. The powdered matter is placed between the steam box and the thin sheet.

856. Figure 184 shows the thermopile and the means of adjusting its position, *a b c d* is the pile, *e* and *f* are two terminals in contact with the poles and to which are connected the wires from the galvanometer. The thermopile is held by two rods *g h*, fixed to a frame *i k*, carrying a pinion, turned by a key, engaging in the rack *l m*. By this means the pile can be adjusted so that the needle of the galvanometer is at zero when the two surfaces, radiating to the opposite faces of the pile, are the same and at the same temperature. The rack is supported by the two rods *p n*, terminating in the threaded rings *q r*, into which are screwed cylinders which pass through the openings *K K* in the tank (fig 178) and are fastened therein by slips of wood.

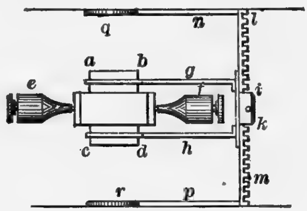

Fig. 184

857. Figure 185 represents the arrangement used to determine the relative radiating powers of different surfaces as needed for the purpose explained in paragraph 788. In the openings *L L L L*, of the apparatus just described, are placed two copper vessels, one heated by steam, the other containing water and so arranged that the water can be heated to a suitable degree; the inner faces of the vessels are covered with the substances of which we wish to determine the

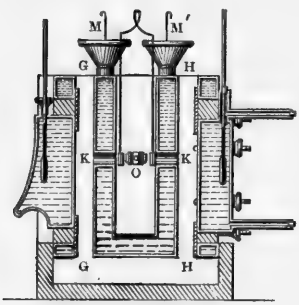

Fig. 185

relative radiating powers, that which radiates the least being on the vessel heated by steam. For glass I used the arrangement shown in figure 178, the opening in the vessel being closed by a thin sheet of glass held in the same way as already described for thick plates of the same material.

858. As in the former methods, we may write an equation between the quantity of heat traversing the plate and that emitted from the exposed surface, and we thus arrive at the very simple formula;

$$C = \frac{e\,Q\,(t'-t'')}{t-t'}\ ;$$

In which C is the conductivity of the material, e the thickness of the plate; Q the value of $K+K'$ modified by the coefficients corresponding to the temperatures (figures 1, 2 and 3), t, t' and t'', the temperatures of the steam, of the outer surface of the plate and of the surrounding air.

859. I have deduced from these experiments the following tables of values of C. These numbers give the quantity of heat in *B. T. U.* which would pass in one hour through a plate of the given material one inch thick, one square foot in area, and of which the two surfaces were at temperatures differing by one degree Fahrenheit.

TABLE OF VALUES OF C.

B. T. U. per hour, per square foot, per inch, per one degree.

SOLID MATERIALS.

	Density.	C.
Marble, gray, fine grained	2.68	28.1
Marble, white, coarse grained	2.77	22.4
Limestone fine grained	2.34	16.8
Limestone do do	2.27	13.6
Limestone do do	2.17	13.7
Limestone coarse grained	2.24	10.6
Limestone do do	2.22	10.2
Plaster, ordinary	2.22	2.67
Plaster do very fine	1.25	4.20
Brick	1.98	5.56
Brick	1.85	4.11
Fir, (wood) transmission perpendicular to fibres	.48	.75

				Density.	C.
Fir, do	do	parallel	do do	.48	1.37
Walnut,	do	perpendicular	do do	.48	.86
Walnut,	do	parallel	do do		1.40
Oak,	do	perpendicular	do do		1.70
Cork				.22	1.15
India rubber				.22	1.37
Gutta-percha				.22	1.39
Starch paste				1.02	3.43
Glass				2.44	6.05
Glass				2.55	7.10

MATERIALS IN A STATE OF POWDER

	Density.	C.
Quartz sand	1.47	2.18
Brick dust—large grains	1.00	1.12
Brick dust—passed through a sieve of silk	1.76	1.33
Brick dust—fine powder obtained by decantation	1.55	1.13
Chalk, in powder, slightly damp	.92	.897
Chalk, in powder, washed and dried	.85	.694
Chalk, in powder, washed, dried and compressed	1.02	.855
Flour of potatoes	.71	.790
Wood ashes	.45	.484
Mahogany sawdust	.31	.524
Charcoal, powdered	.49	.637
Charcoal, powdered and passed through silk	.41	.653
Coke, in powder	.77	1.290

TEXTILE MATERIALS

	Density.	C.
Canvas of Hemp, new	.54	.420
Canvas, do do, old	.58	.347
White writing paper	.85	.347
Gray blotting paper	.48	.274
Calico, new, of any density		.403
Cotton wool, do do		.323
Sheep's wool, do do		.323
Eider down, do do		.315

860. It is important to notice that as the conductivity of textile materials is independent of their density, it follows that

their conductivity is the same as that of motionless air. The conductivity of starch-paste may also be regarded as that of motionless water. I have also noticed, in the case of poor conductors of heat, that dampness greatly increases their conductivity.*

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*TRANSLATOR'S NOTE. Although the experiments described above were made more than fifty years ago there is but little to add due to more recent research. Péclets figures for the conductivity of the metals have been shown to be too low, due probably to the fact the liquids in contact with the surfaces of the metal plate were not frequently enough renewed. This defect would not disturb the accuracy of the experiments on the materials of low conductivity, and it is only these that we use in practical applications of this subject. Péclets figures for these substances have been repeatedly confirmed by more recent experimenters. Péclet evidently made no experiment on the conductivity of motionless air, simply reasoning that it must be the same as that of the textile materials. It has quite recently been proven by direct experiment to be 0.152 which is about one-half of Péclet's value, but in practice we never obtain perfectly motionless air, the process of convection aiding to at least some extent that of conduction. In 879 we find experimental evidence of the value of Péclets figure for the kind of practical application in which we most want to use it.

For further notes on the reliability of this portion of Péclets work the reader is referred to a very interesting paper by Mr. A. B. Reck of Copenhagen, presented in December, 1901, before the American Society of Heating and Ventilating Engineers.

The following table is from Jude and Gossin,—Physics.—1899.

VALUES OF C

Silver	4440	Lead	334
Copper	3192	Ice	17.42
Gold	2100	Snow	2.03
Zinc	888	Water	4.41
Tin	572	Air	0.16
Iron	476		

The ratios between these conductivities for the metals is almost the same as Frantz & Wiedermann's and the value for lead is about three times as large as that found by Péclet.

CHAPTER III

APPLICATIONS OF THE FORMULAS

861. We have already seen (826) that in designating by M, the quantity of heat that traverses in one hour a plate with parallel surfaces, of an area of one square foot, and with its surfaces maintained at the constant temperatures t and t', we have

$$M=\frac{C\,(t-t')}{e} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (a)$$

In this expression e represents the thickness of the plate in inches and C the conductivity, that is to say the value of M for $t-t'=1°$ F and $e=1$ inch.

862. If the body were formed of two superimposed plates, of thicknesses e and e' and conductivities C and C', designating by θ the common temperature of the surfaces in contact, we have evidently when the régime is established:

$$M=\frac{C\,(t-\theta)}{e} \text{ and } M=\frac{C'\,(\theta-t')}{e'}$$

Eliminating θ we have:

$$M=(t-t')\div\left(\frac{e}{c}+\frac{e'}{c'}\right)$$

And for any number of plates:

$$M=(t-t')\div\left(\frac{e}{c}+\frac{e'}{c'}+\frac{e''}{c''}+ \quad . \; . \; . \; . \; . \; . \; . \right) \quad (b)$$

863. By means of the tables (859) and the preceding formulas we may easily compute the quantities of heat which will be transmitted through plates when the temperatures of their surfaces are known. But these temperatures never are known exactly and can only be measured by very delicate experiments, impossible in practical work. Furthermore, in making estimates, it is necessary to have at least an approximate value of the quantity transmitted, in terms of the temperatures of the air inside and outside of the surfaces.

864. Consider first a room enclosed by walls of which one only is exposed to the outside air. Let the temperature of the

air within the room be T and that of the outside air be θ. The régime once established the quantity of heat which would traverse the wall exposed to the air would evidently be equal to that which, in the same time, would penetrate its inner surface, and to that which would escape during the same time from its outer surface. The interior surface would be at a temperature t lower than T and the exterior surface would be at a temperature t' higher than θ. We may admit that the heating of the inner surface and the cooling of the outer take place according to the same laws. Thus in designating by M the quantity of heat transmitted per square foot per hour we would have three expressions for M, one in terms of of the conductivity C of the material of the wall, the two others in terms of the coefficients K and K' of cooling by radiation and contact of air, from which equations we may deduce the values of t and t' in terms of known quantities. But if we employ Dulong's formulas for cooling (794–797) the calculation would be impossible, and even admitting the simpler formulas of 789 and 790 we would be led to an equation of the second degree, rather complicated and extremely difficult to handle. It is better to admit for the cooling and the heating Newton's law (791) which is sufficiently exact for small differences of temperature, and besides in all calculations relative to the transmission of heat one can never expect more than a rather rough approximation because there are circumstances which are impossible to take into account, such as the increase of temperature of the outer surface according to its height above the ground, the action of the wind, of the sun, and so forth. According to this we have:

$$M=\frac{C(t-t')}{e} \quad M=Q(T-t) \quad M=Q(t'-\theta)$$

equations which give,

$$t=\frac{T(C+Qe)+C\theta}{2C+Qe} \qquad t'=\frac{\theta(C+Qe)+TC}{2C+Qe}$$

$$M=\frac{CQ(T-\theta)}{2C+Qe} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

865. From this formula follow several important consequences. If Qe was very small relatively to $2C$ and could be neglected, the formula reduces to $M=\frac{Q}{2}(T-\theta)$ and the value of

M would be independent of C and e, that is to say of the material of the body and of its thickness. This case may occur when the value of e is very small relatively to that of C.

Consider for example lead, the poorest conductor among the metals, and for which $C=113$; supposing the surfaces of the plate to be dull, Q will equal approximately 1.25 and for thicknesses of .395″, .79″ and 1.18″ the values of $2C+Qe$ would be $226+.494$, $226+.988$, $226+1.48$, numbers which differ very slightly. The differences would be even less for the other metals. If we imagine a plate of woolen material, for which the lowest value of C is .323, to have a thickness of .004″, which is about that of a sheet of paper, the value of $2C+Qe$ would be equal to $.646+.005$; the second term being again small relative to the first may be neglected and the value of M would be the same as in the preceding case. Thus a sheet of paper transmits the same amount of heat as a metal plate, of which the thickness may be varied through quite a wide extent.

The case of thin sheets of glass is similar. Since C for glass equals 6.05; $Q=.60+.45=1.05$ and $2C+Qe=12.1+1.05e$ and for thicknesses of .04″, .08″ and .12″, this last expression becomes, $12.1+.042$, $12.1+.084$, $12.1+.126$.

866. If we suppose C very small and the thickness e so large that $2C$ can be neglected in comparison with Qe, the value of M reduces to $\frac{C}{e}(T-\theta)$, consequently it would be independent of the nature of the surface, and inversely proportional to the thickness e; but it is necessary, even for the poorest conductors, that the thickness be very great. For example for woolen cloth with $e=19.7''$ we would have $2C+Qe=.646+1.23\times19.7=.646+24.2$.

867. If we had two walls in immediate contact with one another, admitting that there is no sudden change of temperature in the passage of heat from the first to the second, which is confirmed by experiment, and designating by x the temperature of the junction of the two walls, by e and e' their thicknesses, by C and C' their conductivities, we would have after the régime was established:

$$M=\frac{C(t-x)}{e} \quad M=\frac{C'(x-t')}{e'} \quad M=Q(T-t)$$

$M=Q\,(t'-\theta)$, equations which give,

$$M=\frac{Q\,(T-\theta)}{2+Q\left(\frac{e}{C}+\frac{e'}{C'}\right)}$$

For any number of walls, of thicknesses e, e', e'', and conductivities C, C', C'':

$$M=\frac{Q\,(T-\theta)}{2+Q\left(\frac{e}{C}+\frac{e'}{C'}+\frac{e''}{C''}+\;.\;.\;\right)}\;.\;\;.\;\;.\;(b)$$

868. To illustrate the method of using these formulas we will apply the first *(a)* (864), to a particular case. Imagine a wall built of limestone 32.8 feet high with a conductivity $C=13.71$, the coefficients K and K' being .737 (794) and .40 (figure 7) we have $Q=1.137$; we will suppose $T=59°$ and $\theta=.42.8°$, the value of T is the ordinary temperature of dwellings and that of θ about the average value of the exterior temperature at Paris during the seven months of heating.

The curves of figure 12 show the effect on m, t and t', of the increase in thickness of the wall.

869. The preceding formulas apply to the transmission of heat through a wall exposed to the open air, only when all the other walls of the room may be considered as having approximately the same temperature as the air within the room, a condition which can hardly exist unless the first wall is the only one exposed to the outer air. When all the walls of the room are exposed to the outer air, all the inner surfaces are at temperatures differing very little one from another, and lower than that of the air in the room, and consequently for the same temperature of the inside air, the quantity of heat transmitted under the same circumstances, per square foot per hour is smaller than in the case previously considered. This is the case with isolated buildings with only one room on a story, and also with churches.

870. In the case where all the walls of a room are exposed to the open air, the heating of the inside wall surfaces is effected entirely through the movement of the air, for since these inside surfaces have the same temperature their mutual radiation is without effect. Then, keeping to the preceding notation, we have:

$$M=\frac{C\,(t-t')}{e} \quad M=Q\,(t'-\theta) \quad M=K'\,(T-t)$$

and $Q=K+K'$.

From these equations;

$$t=\frac{Q\,(e\,K'\,T+C\theta)+C\,K'\,T}{C\,(Q+K')+Q\,e\,K'}$$

$$t'=\frac{Q\,(e\,K'\,\theta+C\theta)+C\,K'\,T}{C\,(Q+K')+Q\,e\,K'}$$

$$M=\frac{K'\,C\,Q\,(T-\theta)}{C\,(Q+K')+Q\,e\,K'}$$

871. If the wall was made up of two walls, in immediate contact, of thicknesses e and e' and conductivities C and C' we would have:

$$M=\frac{C\,(t-x)}{e} \qquad M=\frac{C'\,(x-t')}{e'}$$

$$M=Q\,(t'-\theta) \qquad M=K'\,(T-t)$$

and consequently:

$$M=\frac{K'\,Q\,(T-\theta)}{Q+K'+K'\,Q\left(\frac{e}{C}+\frac{e'}{C'}\right)}$$

If there were any number of walls the general formula would be:

$$M=\frac{K'\,Q\,(T-\theta)}{Q+K'+K'\,Q\left(\frac{e}{C}+\frac{e'}{C'}+\frac{e''}{C''}\,\ldots\right)}$$

Applying this case to a wall as in 868 with $C=13.71$, $K=.737$ and $K'=.40$, $Q=1.137$ $T=59°$ and $\theta=42.8°$ we get the results shown by the dotted lines of figure 12.

It is useful to notice that if the walls had a height of 66 feet the value of K' would be .39 instead of .40 and we would obtain practically the same numerical results.

872. The values of M obtained in this last case are much smaller than in the first; this is due, as already explained, to the much lower temperature of the interior surface of the walls.

873. I would remark that, in the two cases just examined, it is necessary to take some precautions in measuring the temperature; if the thermometer were exposed freely to the air, the tem-

perature which it would indicate would be that of the air modified by the mutual radiation between its bulb and the surroundings, and in consequence it would show a temperature lower than that of the air. It is necessary to prevent radiation from the bulb to the walls of the room by surrounding the bulb with several concentric envelopes open at top and bottom, and the air between the envelopes should be rapidly renewed. The effect on a thermometer of the fall of temperature of the inner surface of the walls would evidently be felt by a person in the room, and consequently in order that the sensation of heat should remain the same, the temperature of the air must be increased as the temperature of the inner surface of the walls decreases.

874. The two cases which we have been considering are never precisely fulfilled in practice; in the first case the inner surfaces of the unexposed walls are never exactly at the temperature of the air, on account of their radiation to the other walls and the windows; in the second case there are always portions of the inner surface of the rooms, such as the ceilings and floors which are not exposed to exterior cooling, and often there exist interior walls, such as those separating the naves of churches. These walls are heated by air and radiate to the inner surfaces of the outer walls. Finally in both cases, if there is heating by radiating surfaces, by stoves, radiators or pipes, the rays of heat reach the inner surfaces of the walls and raise the temperature of these surfaces. But, as we shall see further on, we may consider the effects produced by these two cases as the extreme limits of those which are generally met with in practice.

DISCONTINUOUS WALLS

875. So far we have supposed the walls to be continuous, but if they were made up of walls with parallel surfaces, separated by intervals occupied by air, the quantity of heat transmitted might be considerably smaller. If we suppose the intervals to be sufficiently large to permit free movement of air, we may admit without fear of departing very far from the truth, that the quantity of heat transmitted across the air spaces is represesented by $Q\,(x-x')$, x and x' representing the temperatures of the surfaces forming the air space. If the air space was filled up with a material of thickness e and conductivity C the heat transmitted would

equal $\frac{C}{e}(x-x')$; thus we may obtain the value of M, in the two cases that we have considered by replacing in the general formulas $\frac{e}{C}$ by $\frac{1}{Q}$.

Thus the general formula relative to the first case, assuming one and then two air spaces, becomes:

$$M=\frac{Q\,(T-\theta)}{2+Q\left(\frac{e}{C}+\frac{1}{Q}+\frac{e'}{C'}\right)}$$

$$M=\frac{Q\,(T-\theta)}{2+Q\left(\frac{e}{C}+\frac{1}{Q}+\frac{e'}{C'}+\frac{1}{Q}+\frac{e''}{C''}\right)}$$

If the walls were all of the same material and of the same thickness e, and n in number, we would have

$$M=\frac{Q\,(T-\theta)}{2+\frac{n\,Q\,e}{C}+n-1}$$

Assuming a continuous wall of the same total thickness, the quantity of heat transmitted would be:

$$M'=\frac{Q\,(T-\theta)}{2+\frac{n\,Q\,e}{C}+\frac{(n-1)\,Q\,e}{C}}=\frac{Q\,(T-\theta)}{2+\frac{Qe}{C}\,(2\,n-1)}$$

and we would have

$$\frac{M}{M'}=\frac{2+\frac{Qe}{C}(2\,n-1)}{2+\frac{n\,Q\,e}{C}+n-1}$$

876. If we assume the air spaces and the walls each to be .79″ thick, and the walls to be of brick, we would have $Q=1.14$ $C=4.84$ and the ratio:

$$\frac{M}{M'}=\frac{2+.185\,(2n-1)}{2+.185\,n+(n-1)}$$

making n successively equal to

1	2	3	4	5	10

we find for $M \div M'$

1	.75	.64	.57	.53	.43

877. It would seem at first sight, that it would be advantageous to diminish the thickness of the layers of air in order to render it motionless; but then there would be a direct transmission of heat through the air and if the thickness were too small, the transmission would be greater than if the air could move freely. In such an air space the quantity of heat transmitted is given by $(x-x)\left(K+\frac{C}{e};\right)$* and if we suppose $e=.79''$ $\frac{C}{e}$ would equal $\frac{.32}{.79}=.405$ which is practically the value of K' and for a smaller value of e, the factor $\left(K+\frac{0.04}{e}\right)$ would be greater than Q.†

In order that air spaces may diminish the transmission of heat, it is necessary that $\frac{e}{C}$ be always smaller than $\frac{1}{K+\frac{.32}{e}}$.‡

Evidently then the air spaces will be especially advantageous when the surfaces of the walls forming them have a very feeble radiating power.

It results from the preceding that hollow bricks should transmit much less heat than solid ones of the same thickness, and this is perfectly confirmed by experiment.

878. Similar results will be obtained in the second case that we have examined (870), by making the same modifications in the general formula relative to superimposed walls of different materials; there will still be, as in the case which we have just studied, a decrease in the transmission whenever $\frac{e}{C}$ would be larger than the transmission through a sheet of air, augmented by the radiation between the opposite surfaces of the air space.

879. It is now easy to find the loss of heat from a vessel surrounded by envelopes separated by extremely small air spaces.

---

*Radiation $=K(x-x')$

Conduction $=\frac{C}{e}(x-x')$

Then $M=(x-x')\left(K+\frac{C}{e}\right)$

Note that in 875 we assumed $M=Q(x-x')=(K+K')(x-x')$

†If we take the value of C for air given in the foot note to page —, $\frac{C}{e}$ does not equal .4 until e has been diminished to .38″.

‡This may be seen by observing the general formulas of 875.

Thus assuming a single envelope and designating by t and t' the temperatures of the surfaces of the vase and the envelope, and by t'' the temperature of the exterior air, we have:

$$M=(t'-t'')(K_1+K'),\ M=(t-t')\left(K+\frac{C}{e}\right)$$

from which:

$$M=(K_1+K')(t-t'')\left\{\frac{K+\frac{C}{e}}{K+\frac{C}{e}+(K_1+K')}\right\}$$

Assuming two envelopes and designating by θ the temperature of the second surface, we have:

$$\left.\begin{array}{l} M=(t-\theta')\left(K+\frac{C}{e}\right) \\ M=(\theta-t')\left(K+\frac{C}{e}\right) \\ M=(t'-t'')(K_1+K') \end{array}\right\}\text{from which}$$

$$M=(K_1+K')(t-t'')\left\{\frac{K+\frac{C}{e}}{K+\frac{C}{e}+2(K_1+K')}\right\}$$

Increasing successively by one the number of envelopes we find that the coefficient of (K_1+K') in the denominator of the fraction increases successively by one, and we are led to the general formula:

$$M=(K_1+K')(t-t'')\left\{\frac{K+\frac{C'}{e}}{K+\frac{C}{e}+m(K_1+K')}\right\}$$

in which K is the radiation from the interior surfaces, K_1 that of the exterior surface, K' the quantity of heat abstracted from the exterior surface by contact of the external air, C the conductivity of the air, e the thickness of the air spaces, and M the number of envelopes.

If we take $K=K_1=.772$, $K'=.788$ $C=.32$ and $e=.04''$ for the following values of m,

0 1 2 3 4

we find that the relative values of M are,

1 .87 .77 .69 .62

Direct experiments have given,

1 .90 .75 .67 .60

If we create a vacuum between the envelopes, the transmission of heat will only take place by radiation, and the quantity transmitted may evidently be deduced from the preceding formula, by making C therein equal to zero. It then becomes,

$$M=\frac{(K_1+K')(t-t'')K}{K+m(K_1+K')}$$

Assuming the envelopes to be of zinc, we would have $K=K_1=.492$; supposing their number to be ten, and taking $K'=.82$, $t=212$, $t''=59$ we find $M=.78$. To compare this transmission with that that would take place if the interval between the vessel and the outermost envelope were filled with eiderdown, one of the poorest of conductors, assume the interval to be .4″. The formula for the transmission of heat through a plate is $\frac{CQ(t-t'')}{C+Qe}$*, in which C is the conductivity of the material, which for eiderdown is .29, Q the loss of heat from the outer surface which is here .87, and e the thickness which we have taken as .4″. For these numerical values we find the quantity of heat transmitted to be equal to 68.2 nearly ninety times greater than with the envelopes and vacuum.

The means that I have just indicated for diminishing the transmission of heat is the most efficacious that I know. To apply it to two concentric metal cylinders it is necessary to close both ends of the interval separating them with poorly conducting material, then to solder near one end a very small lead pipe, which serves to form the vacuum and is then closed by squeezing it together and melting off the end in the flame of a blow pipe.

This arrangement would be especially advantageous in apparatus destined to make ice.

TRANSMISSION OF HEAT THROUGH WINDOWS

880. We will examine two cases of the transmission of heat through windows; the first will be the same as the case first considered of transmission through a wall, and, the second the case of an enclosure formed entirely of glass.

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* Note that in this case we know the temperature of the inner surface of the wall and of the outer air, and thus $M=\frac{C}{e}(t-t')$ and $M=Q(t'-t'')$. Combining these we get the equation given above.

881. Consider first that the windows are placed in the exposed wall of a room having one only of its walls exposed to the outer air, the inner surfaces of the other walls will be sensibly at the temperature of the interior air. As the rays of obscure heat do not pass through glass, the windows will be heated on one side by radiation from the inner surfaces of the walls and by the contact of the warm air, and will cool on the other side from analogous causes. Admitting that the heating and cooling take place in the same way, for the same excesses of temperature, and remarking that for the small thicknesses of window glass, the quantities of heat transmitted are independent of the thickness, as we have already seen (865), we will have, preserving the previous notation, $M=(T-x)\,Q$ $M=(x-\theta)\,Q$; from which

$$x=\frac{T-\theta}{2} \text{ and } M=\frac{T-\theta}{2}\,Q$$

For heights in feet of:

3.28	6.56	9.84	13.12	16.40

the values of K' (802) being equal to

.492	.453	.437	.427	.420

and the radiation of glass being equal to .596, we find for these different heights and for a difference of temperature of 1° Fahrenheit between T and θ, the following values of M.

.542	.524	.516	.511	.508

The greatest of these numbers is smaller than that I formerly found by direct experiment, because I used a window of smaller height, and did not take all the precautions which I have since recognized as necessary.

If the inside temperature was 59° and the otside 42.8°, that of the glass would be 50.9°, and the quantities of heat emitted in *B T U* per hour per square foot would be, for the heights we have been considering:

8.79	8.50	8.36	8.28	8.24

882. Let us consider now an entirely glazed enclosure heated by warm air, and let us disregard the effect produced by the floor or ground. The glass will only be heated by the air, since all the surfaces are at the same temperature, and their mutual radiation would therefore have no effect. We would then have, pre-

serving the previous notation: $M=(T-x)K'$ $M=Q(x-\theta)$ equations which give:

$$x=\frac{K'T+Q\theta}{Q+K'} \text{ and } M=\frac{QK'(T-\theta)}{Q+K'}$$

We find, as in the preceding case, that for heights in feet of:

3.28 6.56 9.84 13.12 16.40

the quantities of heat transmitted in $B\ T\ U$ per hour per square foot per 1° Fahrenheit difference, are:

.338 .316 .305 .301 .297

For an interior temperature of 59° and an exterior temperature of 42.8°, the quantities of heat transmitted are:

5.48 5.11 4.94 4.87 4.80

These numbers are smaller than those we found in the preceding case (881) because the glass is at a lower temperature.*

883. The two cases which we have just examined, like those relative to the transmission of heat through walls, never actually occur. In the first case the walls opposite the windows are always at a lower temperature than the air, and in the second case there is always a part of the enclosure which is not glazed, and when the heating is effected in part by the radiation from hot surfaces, the rays of heat which fall on the glass increase the quantity of heat which it transmits. But in any case, the quantity of heat actually transmitted is comprised between those which we have computed for the two extreme cases. We will return to this question in speaking of the heating of dwellings.

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* The following note from *London Engineering*, Nov. 1, 1902, is of interest here:

"In cold countries double glazing is sometimes resorted to, in order to reduce the heat lost from a room to the exterior through the windows. Some experiments made by H. Schoentjes, of Ghent, show that there is a certain distance of separation between the glasses, at which the heat lost is a minimum. The glass used in his experiment was .08″ thick and the loss was least when the distance between the opposing sheets was somewhere between 2.6″ to 4.6″. The loss in calm air through one thickness of the glass was at the rate of about .42 $B\ T\ U$ per square foot per hour for each degree Fahr. of the difference of the temperature on the opposite side of the sheet. The experiments were made over a range of 12.6° to 40° Fahr. and the rate of loss was somewhat greater as the difference of temperatures increased but the mean was as stated. With double walls at the best distance apart the rate of loss was about halved. Wetting the outer surface of the glass increased the loss about 39 per cent; whilst if at the same time, a current of air was directed over the outer surface the rate of loss was still further increased up to about .93 $B\ T\ U$ per square foot of glass per hour. The utility of the second layer of glass which can be kept dry and in still air would in such a case as this, be very marked.'

Note that the rate of loss .42 $B\ T\ U$ is about a mean between Peclet's calculations for his two extreme cases. The relative value of the double window appears somewhat greater however.

MULTIPLE WINDOWS

884. In the case of several parallel windows, separated by intervals sufficiently large to allow the air to move freely, the two surfaces of each window are sensibly at the same temperature, and we may obtain the value of M, in the first case that we have considered, by supposing the thickness e, e', e'' equal to zero in the general formula (875). Then for 2, 3, 4 . . n windows, the values of M would be

$$\frac{Q\,(T-\theta)}{2+1};\ \frac{Q(T-\theta)}{2+2};\ \frac{Q\,(T-\theta)}{2+3}\ \ .\ .\ .\ .\ \ \frac{Q\,(T-\theta)}{2+n-1}$$

and the relative values ot these quantities to that of a single window are

$$\frac{2}{3};\qquad \frac{1}{2};\qquad \frac{2}{5}\ .\ .\ .\ .\ .\ .\ .\ .\ \frac{2}{1+n}$$

Curtains, more or less thick, would produce sensibly the same effect. If the distance between the windows was less than .79″, the transmission would be increased, because the transmission through the air $\frac{.32}{.79}$ is equal to the transmission by contact of air and its renewal, and at smaller distances the transmission through the motionless air would be greater.

In the second case, that we considered in regard to walls, the calculation relative to the transmission of heat through windows, would be extremely complicated, because it is necessary to take into account the surfaces of the windows, and we could arrive at no exact conclusions, on account of the influence of floors and ceilings, the effect of which could not be evaluated.

The case first examined evidently gives the maximum transmission ; it is the only one in which we can calculate with sufficient exactitude the quantity of heat transmitted by the windows, and the figures obtained suffice in any case to give a sufficient appreciation of the quantity of heat lost.

TRANSMISSION OF HEAT THROUGH CYLINDRICAL ENVELOPES

885. The case that we will now consider is, for example, that of a metal pipe traversed by steam, and surrounded by some material of low conductivity, in order to diminish the loss of heat from the steam during its passage.

Let M represent the quantity of heat in $B\ T\ U$ transmitted per foot of length, in one hour, R and R' the internal and external radii of the cylindrical covering in feet, t and t' the temperatures of the internal and external surfaces, and θ the temperature of the surroundings. When the régime is established the quantity of heat which passes through the covering is equal to that which at the same time traverses an infinitely thin annular element of radius r, this quantity being equal to the product of the surface $2\pi r$ of this element, the conductivity C' of a thickness of one foot of the material, and the temperature difference dt of the two surfaces, divided by the distance apart dr of these surfaces. We will have then:

$$M=\frac{-2\pi r\,C'\,dt}{dr}\text{; from which } C'\,dt=-\frac{M\,dr}{2\pi r}$$

The minus sign shows that the variations of the temperature and of the radius of the covering take place in opposite directions. Integrating the last equation between the limits t and t' for dt, and R and R' for dr it becomes:

$$C'(t-t')=\frac{M}{2\pi}m\,(\log R'-\log R)$$

$$\text{and } M=\frac{2\pi C'(t-t')}{N}$$

where m is the modulus of the table of logarithms and equals 2.3025 and N represents $m\,(\log R'-\log R)$.

But we also know that $M=2\pi R'\,Q\,(t'-\theta)$: eliminating t' from these equations we have:

$$M=\frac{2\pi R'\,Q\,(t-\theta)}{1+\frac{Q\,R'\,N}{C'}} \qquad \text{(a)}$$

If there are two contiguous coverings, designating by x the temperature of the common surface, we have:

$$C'(t-x)=\frac{M}{2\pi}N;\ C_1'(x-t')=\frac{M}{2\pi}N'$$

and $M=2\pi R''\,Q\,(t'-\theta)$ equations which give, after eliminating x:

$$M=\frac{2\pi\,Q\,R''\,(t-\theta)}{1+Q\,R''\left(\frac{N}{C'}+\frac{N'}{C_1'}\right)}$$

Repeating the calculations for 3, 4 and so on, coverings, we are lead to the general formula :

$$M = \frac{2\pi Q R^{(n)} (t-\theta)}{1 + Q R^{(n)} \left(\frac{N}{C'} + \frac{N'}{C_1'} + \frac{N''}{C_2'} \right)}$$

886. Returning to the formula relative to a single covering:

$$M = \frac{2\pi R' Q C' (t-\theta)}{C' + Q R' m (\log R' - \log R)}$$

if we suppose C' to be very small relatively to $Q R' N$, the formula reduces to

$$\frac{2\pi C' (t-\theta)}{m (\log R - \log R')}$$

an expression independent of Q and decreasing as R' increases; thus in this case the transmission does not change with the nature of the surface. If, on the contrary, the value of C' was very large relatively to the following term we would have $M = 2\pi Q R' (t-\theta)$, an expression independent of C' and increasing in proportion to the increase of R'.

The first supposition is realized with a covering of wool ; the second if we suppose the covering to have almost the conductivity of the metals.

887. The relation of this value of M to the quantity of heat which would be transmitted under the same circumstances by a bare pipe is evidently equal to

$$\frac{C'}{R} \quad \frac{R'}{C' + Q R' m (\log R' - \log R)}$$

An inspection of this formula will show that it is not always advantageous, as regards the loss of heat, to apply a covering, even one of low conductivity, for the value of this expression is not necessarily less than unity; and for a given value of C' it varies with R and R'. There are certain values of C', belonging to bodies reputed to be poor conductors, which give for M values greater than those for a bare pipe, and consequently for these bodies the increase of surface has more effect than the resistance to the transmission of heat through their thickness.

888. Let us take for an example a horizontal cast iron pipe, 2.25″ radius and one foot long, filled with steam at 212° F., and covered successively with different thicknesses of hair

felt. If we assume the temperature of the surrounding air to be 59° F., it results from what we have said in (807) that the quantity of heat emitted per square foot per hour when the pipe is bare is 298 $B\ T\ U$, and for one foot of length this becomes 352.

To find the quantities of heat emitted per lineal foot per hour, by the pipe when it is covered with a layer of hair felt of

.5″ 1.0″ 1.5″ 2.0″ 2.5″ 5.0″

in thickness, we must, in the formula (885), make $C' = \frac{.36}{12} = .03$ $R = .188$ feet and give to R' the successive values, in feet:

.229 .271 .313 .354 .396 .604

To obtain the values of Q, we must remember that $Q = K + K'$, K and K' being the coefficients of cooling by radiation and air contact; if we suppose the covering material to be wrapped with canvas, K will equal .75; and the values of K' we may take from figure 4.

These values of K' are as follows:

.53 .51 .50 .49 .49 .46

then the values of Q are:

1.28 1.26 1.25 1.24 1.24 1.21

The values of N are:

.200 .367 .510 .636 .747 1.170

Substituting the constants in formula b (886) it becomes:

$$M = \frac{28.84 \quad Q R'}{.03 + Q R' N}$$

and we obtain the following results:

Thickness of covering in inches.	Value of M.
.5	$\frac{8.45}{0.89} = 94.9$
1.0	$\frac{9.86}{.155} = 63.6$
1.5	$\frac{11.30}{.230} = 49.2$
2.0	$\frac{12.65}{.309} = 41.0$
2.5	$\frac{14.12}{.396} = 35.7$
5.0	$\frac{21.08}{.891} = 23.7$

If the coverings were enveloped with a sheet of tin we would have $K = .09$, and consequently the values of Q would become:

.62	.60	.59	.58	.58	.55

and we would find for the values of M:

70.7	52.2	43.0	37.0	32.9	22.4

The influence of the feeble radiation from the tin surface diminishes as the thickness of the covering increases, because the value of C' relatively to the term $Q R' N$ is diminishing and because if C' could be neglected, the value of M would be entirely independent of Q.

889. In the preceding calculations we have taken $C = .36$ which gave .03 for C'; if we suppose a conductivity two, four, eight. . . . N times as large, it would suffice, to obtain the corresponding values of M, to multiply the numerators of the fractions in the preceding table of values of M, by 2, 4, 8 . . . . N, and to add to the denominators:

$$.03, \quad .09, \quad .21, \quad . \; . \; . \; . \; . \; . \quad .03\,(n-1)$$

It is in this way that we have obtained the numbers in the following table. These correspond to the same values of R' and to the same temperatures. The quantity of heat emitted from the bare pipe would of course remain 352 $B\ T\ U$.

Quantities of Heat in $B\ T\ U$ transmitted per foot run per hour by a horizontal pipe 4.5″ outside diameter, heated to 212° and with external air at 59° and covered with materials of different conductivities and different thicknesses:

Value of C	Value of C′	Thickness of covering in inches. .5	1.0	1.5	2.0	2.5	5.
		B. T. U.					
.36	.03	94.9	63.6	49.2	41.0	35.7	23.7
5.76	.48	251.	261.	265.	266.	267.	252.
11.52	.96	266.	292.	312.	325.	341.	372.

890. We see from this table that the values of M decrease very rapidly with increase of thickness when the conductivity is very low; that the variations are very small for values of C in the neighborhood of 5.76, and that for greater values of C the values of M increases with the thickness of the covering. For pipes of

other diameters, the same phenomena recur, but at other thicknesses.

891. *.

892. In all that precedes in regard to cylindrical coverings, I have supposed the value of Q to be constant, that is to say that Newton's law of cooling held true for any excess of temperature; but this is not the case as we have seen in 805, and the value of Q increases quite rapidly with the excess of temperature; thus the different values of M calculated by the formula of 885, can only be considered approximations, the more exact the smaller they are, since the excess of temperature decreases with M. But it is easy in any particular case to obtain a value of the quantity of heat which is very close to the truth. Suppose that we have first calculated the value of M by the formula (885); dividing this result by $2\pi R' Q$ we will have the temperature t' of the surface, and by means of the curves of figures 1, 2 and 3, we may deduce a new value Q_1 of Q, then new values M_1 and t_1, and we may repeat the process, until two consecutive values of M are the same.

I will take for an example a horizontal cast iron pipe 4.5″ outside diameter covered with one-half inch of hair felt, filled with steam at 212° and surrounded by air at 59°. We have already found that for this case M equals 94.9. Since the surface per foot run is 1.18 sq. feet and Q was equal to 1.28 we have

$$(t'-\theta)=\frac{94.9}{1.18\times 1.28}=62.8^\circ$$

We know that $K=.75$ and $K'=.53$ then from figures 1, 2 and 3,

$$Q_1=.75\times 1.22\times 1+.53\times 1.25=1.58$$

Then $M_1=102$ and $(t'-\theta)_1=54.7^\circ$ then $Q_2=1.55$ and $M_2=101.5$

Thus the value of M is 101.5 instead of 94.9, not a large difference, and it would have been much smaller if the covering had been thicker.

893. In general when the pipes are of small diameter, the second term of the denominator of the expression for M is very large in relation to the first term, at least when the covering is a

*The table given in 891 is not reproduced as it has but little value for modern conditions.

poor conductor of heat. In this case we see that the denominator, like the numerator is nearly proportional to Q, and therefore the value of Q has only a small influence. Thus the numerical results that we have given may be considered sufficiently accurate for many practical purposes, but this would no longer be true if, for the same difference between the inside and outside radii, the value of the inside radius was very large. In this case we find a notable difference between the direct calculation and the method of approximation which I have just indicated.

894. I will take a steam boiler for an example. The surface is generally covered with a poor conductor of heat, and it is important to recognize the influence on the loss of heat of the different materials which may be employed, I will assume that the cylinder forming the boiler has a diameter of 3.28 feet; the quantity of heat emitted per hour per square foot is given by the following formula:

$$M = \frac{Q\,C'\,(t-\theta)}{C' + Q\,R'\,m\,(\log R' - \log R)} \quad . \quad . \quad . \quad (a)$$

Assume as before $Q = .43 + .75 = 1.18$ and that the covering material is sawdust mixed with a little clay and cows hair to render it plastic; we may take $C = .80$ and therefore $C' = .067$.

We will suppose the boiler to be filled with steam at 212° and the surrounding air to be at 59° Fahrenheit.

With the following thicknesses of the covering

.4″	.8″	1.2″	1.6″	2.0″	. . (1)

the formula (*a*) gives directly for M

113.0	81.8	63.7	52.6	44.7	. . (2)

and by the method of approximation indicated (892)

132.0	89.5	67.4	54.5	45.8	. . (3)

If the surface of the covering is finished by a sheet of Russia iron, we have by the formula

63.8	52.7	45.0	38.8	34.2

and by the method of approximation,

82.7	63.0	51.0	42.8	36.5	. . (4)

It follows from these numbers and from the fact that the emission from the bare surface is 260, that the coverings reduce the transmission to,

.509	.344	.259	.210	.176	. . (5)

and the same coverings covered with Russia iron:

.318 .243 .196 .165 .141 . . (6)

The influence of the Russia iron is very great, but it diminishes with the thickness, for the relations of the corresponding numbers of series 5 and 6 are:

.63 .71 .76 .79 .80 . (7)

As the steam pressure increases the percentage of saving due to a covering somewhat increases.*

TRANSMISSION OF HEAT THROUGH SPHERICAL ENVELOPES

895. Preserving the same notation as before, we find

$$M = -\frac{4\,\pi\, r^2\; C'\, d\, t}{d\, r}; \text{ or } 4\,\pi\; C'\; d\, t = -M\frac{d\, r}{r^2}$$

and integrating between the limits t and t' for t and R and R' for r we find

$$4\,\pi\; C'\;(t - t) = M\left(\frac{1}{R} + \frac{1}{R'}\right)$$

$$\text{whence } M = \frac{4\,\pi\; C\, R\, R'\;(t - t')}{R' - R}$$

But since $M = 4\,\pi\; R'^2\; Q\,(t - \theta)$, we may eliminate t and obtain;

$$M = \frac{4\,\pi\, C'\; Q\, R R'\;(t - \theta)}{C'\, R + Q\, R'\;(R' - R)}$$

an equation in which M represents the quantity of heat in *B. T. U.* per hour emitted by the total surface of the sphere. To obtain the emission per square foot, we must evidently divide M by $4\,\pi\; R'^2$.

DIFFUSION OF HEAT

896. In all that precedes we have only considered the transmission of heat through a body after the establishment of a permament régime of temperature. In this case the laws of the transmission are very simple, and the formulas that we have given

*For a more modern example we may take a Scotch boiler twelve feet in diameter, under 180 pounds steam pressure, with the surrounding air at 100°, and covered with two inches of magnesia. The values of C', K, and K', will be .04, .74 and .42

By the formula $M = 53.7$ but by successive approximations thus becomes 55.7.

If we jacket the covering with Russia iron the formula gives 44.7 and successive approximations brings this to 48.2.

The heat loss from the bare boiler would be (by 807) 685 B. T. U. per hour per square foot. The plain covering has a loss of only eight per cent of this amount and when jacketed with Russia iron only seven per cent.

allow the computation of the quantities of heat transmitted in the different cases which ordinarily present themselves. But before the establishment of the régime, in bodies limited by two surfaces of which one receives the heat and the other emits it, and during the entire duration of heating, for bodies unlimited in one direction, the temperatures of different points vary with their position and with time, according to very complicated laws, which depend at the same time on the form of the body, on the conductivity of the material of which it is constituted, on its specific heat and on its density; thus bodies formed of materials which are the best conductors of heat are not always those which disperse it most rapidly, because the dispersion depends on the relation between the conductivity of the material and its specific heat.

897. It results from mathematical calculations, too complicated to give here, that if we consider a plane surface of unlimited extent, maintained at a temperature T, and beneath this surface a homogeneous body, of very great thickness, at the temperature 0° Centigrade, after one minute the temperatures at distances of

	.04″	.4″	4.″	40.″
will be for sand	$0.988T$	$0.887T$	$0.154T$	$0.000T$
" lime stone	$0.997T$	$0.973T$	$0.745T$	$0.001T$
" iron	$0.999T$	$0.992T$	$0.924T$	$0.339T$
" coarse grained marble	$0.999T$	$0.993T$	$0.938T$	$0.439T$
" plaster	$0.996T$	$0.962T$	$0.624T$	$0.000T$
" motionless water	$0.993T$	$0.939T$	$0.399T$	$0.000T$

898. The formula by which these numbers have been computed is a rigorous deduction from the fundamental principle of the transmission of heat and this principle has been proven by too great a number of experiments to allow any doubt of its exactitude; but in establishing this formula the effects of expansion and of variation of specific heat with temperature have been neglected; however, since for solid bodies the expansion, variation of specific heat and variation of conductivity are small we may regard the formula as very approximately representing the facts. Thus the numbers which we have given show with what rapidity heat diffuses itself through bodies even when of low conductivity, after the establishment of a permanent régime of temperature.

899. If we apply the formula to air supposedly motionless, as it would be if heated from above, we would certainly obtain but a rather vague approximation, on account of the large expansion that it would experience and the unknown variations of its conductivity with increase of temperature. However, as the results of the calculation may at least give an idea of the rapidity with which heat disseminates itself in air we will indicate them. After one minute and at distances:

.04″	4.″	4″	40″

the temperatures given by the formula are:

$0.999T$	$0.996T$	$0.960T$	$0.620T$

If the formula employed was truly applicable to air it would result that the dispersion of heat in air would be grater than in any other substance; but we may certainly conclude from these figures that the diffusion of heat in air takes place with great rapidity. Furthermore this fact explains many phenomena which appear very strange.

900. In churches heated by warm air escaping from a number of openings in the floor, the temperatures of the air at heights of 6½ feet and 66 feet differ by less than two degrees as has been proven at La Madeleine and Saint-Roch.

In the cooling of bodies by contact of air, the quantity of heat emitted diminishes very slowly with increase of height of the body, which can only be explained by the rapid diffusion of the heat in the surrounding air. Another result of this fact is that in the heating of rooms by open fire places, not only a part of the radiation is utilized but also that portion of the heat produced which is transmitted by diffusion to the surrounding air.

901. M. Darcy, chief engineer of the *ponts et chaussées* made very interesting experiments on the cooling of warm water passing through pipes buried in the ground. The total length of the cast iron pipe was 7610 feet. Its diameter varied between 6.4″ and 9.84″. The weight of water passing in one second was 8.12 pounds, the cooling was from 80.16° to 69.64° that is to say 10.52°, the loss of heat per second in *B. T. U.* was then $8.12 \times 10.52 = 85.5$ and per hour $85.5 \times 3600 = 307800$; and as the pipes had a total surface of 16450 square feet, the quantity of heat in *B. T. U.* per square foot per hour was 18.68 for a mean temper-

ature of 74.8°. The time employed by a particle of the liquid in traversing the entire length of the pipe was eight and one-half hours. The liquid when motionless cooled 9.9° in seven hours. It is probable that the transmission is proportional to the excess of the temperature of the pipe above 32°, and for steam would be between 75 and 100 *B. T. U.*

INFLUENCE OF THE VARIATIONS OF EXTERIOR TEMPERATURE ON THE QUANTITY OF HEAT TRANSMITTED THROUGH WALLS

902. In what we have said regarding the transmission of heat through bodies of low conductivity, we have supposed the régime to have been established, and consequently that the interior and exterior temperatures were constant; ordinarily the heating is regulated so that the interior temperature does not change, but the transmission is always affected by the variations of exterior temperature. These variations are of two sorts; the general decrease and increase of the mean exterior temperature during the season of heating, and the accidental variations which manifest themselves almost every day. We will examine the influence of these two in turn.

In our climate, * heating generally is necessary from the first of October to the end of April, and during these seven months, the mean exterior temperatures, deduced from the records of ten years, are

Oct.	Nov.	Dec	Jan.	Feb.	Mar.	Apr.
51.8	45.1	37.4	36.1	39.7	43.9	50.9

If we assume that the interior temperature is maintained at 59°, that the walls are all exposed to the outer air, and that their thickness is 39.37″, the total quantity of heat transmitted per square foot during the total duration of the heating, admitting that the régime is constantly established would be (871.);

$$2.59 \times 210 \times 24 = 13050 \; B.\ T.\ U.\dagger$$

and the total heat above 32° contained in the wall at 59°;

$$3.28 \times 62.4 \times 2.2 \times 0.2 \times 27 = 2430.$$

This last quantity being less than two-tenths of the first, and the cooling of the wall being never complete, it is easy to see that if the variations of temperature took place gradually, without

*Paris, France.

†The average exterior temperature for the seven months is here taken as 42.8°

sudden oscillations, that whatever the law according to which the wall cooled during the first part of the winter, and heated during the second part, the quantities of heat emitted and absorbed by the wall, could have but a slight influence on the transmission, according to the hypothesis of a constantly maintained transmission. We see furthermore that during the decrease of the exterior temperature the cooling of the walls diminishes by a small amount the quantity of heat which must be furnished in order to maintain the interior temperature, and that during the increase of the exterior temperature, there will be more heat to be furnished to reestablish the original régime throughout the wall.

903. According to what we have just said, the curve of mean monthly temperatures of the heating months presents but one minimum; but each day there are several variations in opposite directions so that the actual curve of temperatures shows a great number of sinuosities around the curve of mean temperature. These variations act directly on a heated room through the windows, because the windows take almost instantaneously a temperature which is a mean between the interior and exterior temperatures. It is otherwise with the walls; they furnish, when the exterior temperature falls, a certain quantity of heat, and when the exterior temperature rises again to the original point, they absorb the same quantity of heat, so that the quantity of heat to be furnished to maintain a constant interior temperature, varies much less rapidly than the exterior temperature. Since these variations are equal and of opposite signs in regard to the curve of mean temperature, in whatever way the partial cooling and heating of the wall takes place, the losses and gains end by compensating one another, and the total expenditure of heat during the heating season remains the same as if the exterior temperature had followed the curve of mean monthly temperatures, or as if the exterior temperature had remained constant at the mean temperature for the whole season. This is confirmed by experience.

904. The phenomena produced in walls by sudden variations of the exterior temperature are very complicated. If a fall of temperature takes place there is an increase of loss from the exterior surface, and a decrease in its temperature which spreads

little by little even to the inner surface, and if the new temperature of the exterior air lasts sufficiently long, a new régime is established in the wall. During this interval the temperatures of the different points of the walls would undergo changes which it would be actually impossible to calculate, since the calculations would be even more complicated than those regarding the transmission of heat in an unlimited medium at constant temperature (897). But, since walls are rarely more than twenty inches thick, and as the dissemination of heat through bodies, even of the rather low conductivities of materials of construction, takes place with great rapidity, and as the difference of temperature of the two surfaces are not generally more than a small number of degrees, we may assume that, during all the changes of temperature which precede the establishment of the new régime, the temperatures of the different points of the wall increase uniformly from the exterior to the interior. This supposition is never realized, but it allows us to follow approximately the phenomena which accompany a fall of the exterior air temperature.

Consider a wall belonging to a room of which none of the other walls are exposed to the exterior air; assume as in paragraph 868, $T=59°$, $\theta=42.8$, $C=13.71$ and $e=19.70$, we will have $t=54.62°$, t' $48.19°$ and $M=5.08$. If the exterior temperature became 32°, the formula *(a)* (864) would give $t=51.56$, $t'=39.42$, and $M=8.45$, the quantity of heat lost by the wall per square foot in passing from the former régime to the latter would be:

$$1.64\times 62.4\times 2.22\times .21\left(\frac{54.62+48.19}{2}-\frac{51.56+39.42}{2}\right)=283 \; *$$

and as this cooling takes place while the temperature of the outer surface falls from 48.19 to 39.42, the cooling is decreasing; admitting the hypothesis of a uniform variation of temperature, this cooling would take place in the same time as if the excess of temperature of the outer surface was equal to $\frac{16.19+7.42}{2}$ or 11.81; and since for an excess of temperature of 16.19, the loss of heat

*This figure is just twice that given in Péclet although the equations are otherwise identical. This error appears in both the later editions.

per hour is 5.98, * the cooling in question would take place in $\frac{283 \times 1.37}{5.98} = 64.8$ hours †

This supposes the interior temperature to be maintained at 59°, and the cooling of the wall to take place in the way that we have assumed; but in reality the cooling would be much less rapid, because the temperatures of the outer surface would be much lower than we have admitted and because the temperatures of the different layers of the wall would succeed each other according to a different law which would also aid in retarding the cooling.

905. We see from this that if the cooling of a room took place through the walls alone, the variations of the exterior temperature would manifest themselves within very slowly, and feebly. But rooms have always glazed windows, and as the glass almost instantaneously assumes the mean of the inner and outer temperatures, we must in order to maintain a constant temperature, supply an increased quantity of heat which will vary with the exterior temperature and is in general very much greater than that which would result from the transmission of heat through the walls.

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*When the loss was 5.98 B. T. U. the exterior temperature was 42.8° and the temperature of the outer surface was 48.19°; this is an excess of temperature of 5.39° not 16.19°.

†This figure is just twice that given in the original text for the reason explained above.

The reasoning in this paragraph is certainly difficult to follow. We may consider the problem in another way. Péclet appears to admit that during the cooling of the wall the mean temperature of the outer surface is a mean between its temperatures at the beginning and end of the process. Then we may assume the same to be true for the mean temperature of the inner surface. Then the difference between the emission from the outer surface and the absorption by the inner surface per hour will be the mean amount of the hourly cooling of the wall. Then the total amount of cooling, which we have already calculated, divided by this quantity, will give the time of cooling.

The mean temperature of the outer surface is $\frac{48.19 + 39.42}{2} = 43.81°$

and its excess over the outer temperature is $43.81° - 32° = 11.81°$.

Taking Q as in 868 = 1.14 we have; *B. T. U.* emitted per hour per square foot = $1.14 \times 11.81 = 13.47$.

The mean temperature of the inner surface is $\frac{54.62 + 51.56}{2} = 53.09$

The excess is $59 - 53.09 = 5.91$ and; *B. T. U.* absorbed per hour per square foot = $1.14 \times 5.91 = 6.74$.

Then the mean hourly loss of heat by wall = $13.47 - 6.74 = 6.73$ and the duration of cooling = $\frac{283}{6.73} = 42$ hours.

Consider for example, a room with but one wall exposed to the outer air, with 4.305 square feet of glazed windows and 64.6 square feet of walls of 19.7 inches thich; the interior temperature being 59° and the outer temperature 42.8° the total quantity of heat transmitted will be; (868 and 881).

$$43.05 \times 8.5 + 64.6 \times 5.05 = 366 + 326 = 692.$$

If we suppose the exterior temperature to fall to 32°, the quantity of heat transmitted by the windows will rise immediately from 366 to 611, whilst the transmission of heat through the walls will rise very slowly in 32 hours, * from 326 to 546, and as a matter of fact the rise will be much slower. Thus the windows have a much greater influence than the walls on the variation of the interior temperature or on the quantity of heat which must be supplied to maintain this temperature, at least unless the walls are very thin and their area very large relative to that of the windows.

906. As it is important to have a clear idea of the variations of temperature which take place at the surfaces of walls during the heating season, as well as the quantities of heat transmitted and the quantities of heat contained in the walls, I have computed these different elements for walls of 19.70, 39.37 and 59.07 inches in thickness according to the formulas (870) which assume all the walls exposed to the outer air. I have taken $C = 13.71 K = .737$ and $K' = .40$ whence $Q = 1.137$; and have assumed the specific gravity of the stone to be 2.2 and its specific heat to be .2. Then the quantity of heat contained per square foot of wall at the temperature v will be

$$1 \times \frac{e}{12} \times 62.4 \times 2.2 \times 2\ v = 2.288\ e\ v$$

When the temperatures vary uniformily from t to t', between the two surfaces, the quantity of heat contained in the wall, reckoned from $O°$ would be $2.288\, e \frac{t + t'}{2}$; we will designate this quantity by A and we will have, calling the interior temperature of the room T and the exterior temperature θ:
for $e = 19.7$ inches.

*See foot-notes to 904

$t = 48T + .52\theta$, $t' = .18\,T + .82\theta$, $M = .21\,(T - \theta)$, $A = 45\,(.33\,T + .67\theta)$

for $e = 39.37$ inches.

$t = .60T + .40\theta$, $t' = .14T + .86\theta$, $M = .16\,(T - \theta)$, $A = 90\,(.37\,T + .63\theta)$

for $e = 59.07$ inches.

$t = 68T + .33\theta$, $t' = .12T + .89\theta$, $M = .13\,(T - \theta)$, $A = 135\,(.40\,T + .60\theta)$

INTERMITTENT HEATING

907. We have hitherto supposed the heating to be continuous ; but it is often suspended during the night and at other times it only takes place during a very limited time : we have then two cases to consider, the loss of heat due to the suspension of the heating at night, and the quantity of heat which must be furnished in order to maintain a room at a certain temperature during a certain length of time.

HEAT LOST BY WALLS DURING THE SUSPENSION OF HEATING

908. During this suspension which generally takes place at night, the heat emitted from the outer surface of the walls is the cause of a certain amount of cooling throughout their mass and consequently a certain cooling of the interior which is added to that arising from the windows. This cooling of rooms during the intervals between heating is a very important question, unfortunately very complicated, but in regard to which theoretical considerations may nevertheless lead to some useful practical conclusions.

909. Considering the simplest case, that in which all the walls of a room are exposed to the outer air ; all the interior surfaces will be sensibly at the same temperature, and the heat emitted by the walls will be solely that contained within them. I have attempted to calculate the temperatures of different points of the wall at different periods of its cooling by employing the principles and formulas of Fourier *(Traité analytique de la Chaleur)*; a very simple equation giving the temperature of any point as a function of all the given quantities of the question is in this way easily arrived at. This equation contains arbitrary constants of which the values are easily determined on the assumption that at the beginning of cooling, the temperatures at the different points of

the wall follow one another according to the régime of cooling; but, to determine them on the assumption that at the beginning of cooling, the temperatures follow one another according to the régime of transmission, we would be lead to very long calculations, to formulas composed of an infinity of terms and which would not really be of any practical value. However, we may admit the following facts to have been well demonstrated both by experience and calculation.

1st. When a wall is left to its own cooling, the temperature of its outer surface falls rapidly, the more so the smaller its conductivity and its specific heat. The line of temperatures of the points within the wall changes from the straight line of regular transmission, to a curve intersecting the straight line at distances increasing with the time. The curve approaches more and more, as time goes on, to that curve which calculation would give for the case of regular cooling on the assumption that at the beginning of cooling the temperature of the points within the wall follow one another according to the régime of cooling.

2nd. The quantity of heat transmitted by the wall, resulting solely from its own cooling, is never more than a very small fraction of that which it would allow to pass in a regular régime of transmission.

3rd. The quantity of heat lost by a wall in ten hours is generally but a small part of the heat contained in the wall at the beginning of cooling, at least for walls as thick as 19.7 inches; for example for $T=59°$, $\theta=42.8°$, $t=50.7°$, $t'=45.8°$, $M=3.36$ (871), the quantity of heat above 32° contained in the wall per square foot of surface would be $1.64 \times 62.4 \times 2.2 \times .2\ (49-32) =764$. Whilst the quantity of heat that would be lost in ten hours by regular transmission would be only $3.36 \times 10 = 33.6$, and the quantity lost by cooling would be much smaller.

4th. Cooling, during suspension of heating, results principally from the transmission through the glass of the windows and the infiltration of air through the cracks of doors and windows when the room is provided with a chimney.

TEMPORARY HEATING OF A ROOM

910. When a room is only to be occupied for a very short

time, we may heat it by warm air alone or by warm air and radiation; in both cases the loss of heat is made up of that transmitted by the windows and that absorbed by the walls.

The heat received by the walls through radiation or through the currents of air cooled by contact with their surfaces, is propagated step by step throughout their thickness according to extremely complicated laws. When the air of the room has been brought to a certain temperature and the heating ceases, the cooling of the air takes place with rapidity, because the heat is absorbed by the walls and windows, not alone by the air contact action but also by the diffusion of the heat through the mass of air; thus, to maintain the air at a sensibly constant temperature, the heating must be continuous.

NOTES ON THE USE OF THE FORMULAS

911. None of these calculations which we have just been making in regard to the transmission of heat, can be considered rigorously exact. Those relating to elementary transmission rest on two hypotheses which are only true within certain limits; Newton's Law of cooling, which is only approximate even for small differences of temperature, and the supposition that all points of a body exposed to the air are at the same temperature; which is not exact, for the lower portions are always at a lower temperature than those above. In regard to the formulas representing the transmission of heat through walls the two assumptions that we have made (864 and 870) are actually only extreme cases, between which any actual case will be found to lie. But we must not deceive ourselves in regard to the practical importance of rigorous exactness in the formulas or precision in the calculations; the lightest movement of the air has a great influence on the quantity of heat which it carries away and for bodies exposed to the open air the accidental and periodical variations which it experiences never permit the existence of a permanent régime in the interior temperatures. In the preliminary calculations we are obliged to use figures which are not perfectly exact for any of the materials except textile materials, for they vary with the density, for stones with the state of their crystallization, for wood with the direction of the fibres. Thus we can only regard the results of the calculations as sufficient approximations for the guidance of engineers. But heating and ventilating apparatus has always under ordinary circumstances an excess of power, because it should be calculated for the most unfavorable conditions, and this excess of power is destroyed, according to the indications of thermometers and anemometers, by the adjustment of registers or the supply of fuel; thus the uncertainty of the calculation, which is always within sufficiently narrow limits, is taken care of by the excess of power of the apparatus, an excess of power which is only necessary in cases of rare occurrence and of short duration. This is not at all

peculiar to heating apparatus; in all practical applications of theory, the calculations always depend on certain given quantities or conditions which are never more than approximately known, and every apparatus or machine, for whatever purpose it may be destined, should possess an excess of power or of strength designed to cover the uncertainties of calculation, or to satisfy exceptional circumstances.

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