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M.	D.
0	1
3	1
6	3
9	3
12	3
15	4
18	4
21	2·5
24	2·5
27	2
30	1·5
33	1·5
36	1·5
39	1·5
42	1·5

The direction of the current was S.U. Several small weights were added to the can; but the deflection remained steady at 1·5. In copper wire, no fall in the deflection was observed when the weight was left suspended for some time.

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XXVI. *On the Influence of Temperature on the Passage of Air through Capillary Tubes.* By FRANCIS GUTHRIE, LL.B.*

IN using "Marsh's" apparatus for testing for arsenic, it may be noticed that, when heat is applied to the exit-tube to decompose the arsenuretted hydrogen, the liquid rises in the tube which supplies the sulphuric acid, thus leading to the supposition that the passage of the gas through the exit-tube is checked by the increase of temperature, thereby producing increased pressure. This observation suggested the following experiments on the effect of heat on the passage of gases through capillary tubes.

The apparatus used was as follows:—From a vessel, A, water drops into a funnel, *b*, causing a continued overflow.

* Communicated to the Physical Society, April 13, 1878. A note of the results was communicated to the British Association, 1876.

The overflow falls into the concentric funnel B, and escapes by the tube C. The middle of the funnel-tube is removable, and

Fig. 1.

may be replaced by tubes of any required lengths. The lower end of the funnel-tube passes air-tight through the cork of a bottle, V, and has hanging from its end a little thimble of glass, D. By this means, whatever amount of water has entered V, the pressure in V is that due to the difference of height of the water in *b* and D. The air from V is dried by two chloride-of-calcium tubes, F and G, and then passes through the experimental capillary tube H, which can be heated. Thence it passes down the tube I and is collected over water in the tube J, which has a marked stricture. The vessel in which J stands is always overflowing.

It was found that the utmost attention was required to keep the air perfectly dry. A joint of caoutchouc in water is found to be porous to water near its boiling-point, the water probably penetrating as a vapour. As the slightest intrusion of water would vitiate the experiment, paraffin was used in such cases.

The first point to be decided on was, whether heating a current affected its rate of motion independently of its friction. At first sight this seemed not to be impossible; the expansion of the air while its temperature is being raised might, it was thought, react on the air behind it and thus check its outflow. Experiments, however, showed that this was not the case, and

that the effect of heat in checking the current is due solely to its influence on gaseous friction.

It was found that the amount of air passing down a given capillary tube varies approximately in the inverse ratio of the square of the absolute temperature, and directly as the difference of pressure at the two ends of the tube.

Neither of these relationships, however, is quite exact; the following formula more nearly expresses actual results. Calling t the time required to fill with air a vessel of given capacity, and T being the absolute temperature reckoned from -273° C., and denoting by p_1 and p_2 the pressures at the ends of the tube,

$$t = \frac{\alpha T^2}{p_1 - p_2} \left(1 + \frac{\beta}{T(p_1 - p_2)^n} \right).$$

where α is a small fraction depending probably on p_1 .

The facts that the time varies approximately as the square of the absolute temperature, and is not exactly in inverse proportion to the difference of pressure, are worthy of notice; and their theoretical investigation will throw some light on the molecular theory of gases. The fact that the temperature affects the time according to the square of the absolute temperature is consistent with known molecular laws. It has been shown that the viscosity of air and its consequent shearing friction is in proportion to T . And it is obvious from the fact that the volume of a given mass of air is directly as its absolute temperature, that the time required for the passage of a given quantity of air through a given tube at a given pressure should vary as T^2 .

More anomalous are the results that the velocity does not exactly follow the simple law that the rates of passage at a given temperature are in proportion to the difference of pressures at the ends, but that the time of passage of a given mass of air is shortened by increased pressure in a somewhat greater proportion than the increase of pressure. The deviation from the law of inverse proportion is only slight, and obviously belongs to a term having a small absolute factor. But an inspection of the results will show that its existence is unmistakable.

To examine the effect of simply raising the temperature, the following experiments were made:—

(1) The current was heated in a wide tube before reaching the capillary tube, being afterwards cooled again to the temperature of the outer air. *Result*:—the time of passage of a given mass of air was slightly increased.

(2) The current was heated after passing the capillary tube. *Result*:—a slight decrease in the time of passage of a given volume. The decrease was only such as might be accounted for from the fact that the air was not completely cooled again.

(3) The heating and cooling of the current in the capillary tube. *Result*:—an increase of time apparently proportional to the length of the tube heated.

The following are the experiments:—

(1) Whole current at atmospheric temperature 22° C.

$$(a) \quad t = 659''$$

$$(b) \quad t = 656'' \quad \text{Mean } 657''\cdot 5.$$

The current was then heated to 100° C. in a wide tube before entering the same capillary tube.

$$(a) \quad t = 670''$$

$$(b) \quad t = 668'' \quad \text{Mean } 669''.$$

The slight increase of time here indicated was probably due to the fact that the air current had not altogether regained its normal temperature before reaching the capillary tube.

(2) Whole current at atmospheric temperature 21° C.

$$(a) \quad t = 157''$$

$$(b) \quad t = 156'' \quad \text{Mean } 156''\cdot 5.$$

The current was then heated to 100° C. in a wide tube after passing through the capillary.

$$(a) \quad t = 153''$$

$$t = 155'' \quad \text{Mean } 154''\cdot 0.$$

(3) Capillary tube partly immersed in a paraffin-bath at 200° C. The end cooled to 22° C.

$$t = 10055''.$$

More of the tube being heated,

$$(a) \quad t = 1098''$$

$$(b) \quad t = 1094'' \quad \text{Mean } 1096''.$$

The effect of heating and cooling of the same current in different tubes in the same circuit was then examined. The

same tubes were timed separately and in conjunction at the same and at different temperatures.

Tube.	Temperature.	Time.
1	24.5 C.	60"
2	"	57
3	"	58
1	100	89
2	"	81
3	"	82
1 + 2	24.5	117
"	100	173
1 }	100 }	203
+ 2 + 3 }	21 }	
1 + 2 }	100 }	228
3 }	21 }	

These results show that the resistance of the sum is very nearly the sum of the resistances, whether all the tubes are at the same temperature or some at one temperature and some at another.

In order to ascertain whether the rate of passage followed any special law at the beginning or end of the tube, the time of the passage of a given mass of air thrust through a given tube at a given pressure and temperature was ascertained; the tube was then divided into parts, and the time of the passage of the same bulk of air through each part was measured.

	20° C.	100° C.
Entire tube	372.5	563
Part 1	89.5	133.3
" 2	117.5	180.0
" 3	63	96.5
" 4	101	152
" 1 + 2	208.5	315.6
" 3 + 4	165	246.6

From this Table it is seen that, within the limits of experimental error, the time taken for the passage of a given bulk of air through the entire tube is equal to the sum of the times taken for the passage of the same amount of air through each of its parts.

A similar experiment with a tube divided into a greater

number of parts was then made. The original tube was about 600 millims. long.

$$(a) \quad t = 85''$$

$$(b) \quad t = 83'' \quad \text{Mean } 84''.$$

The tube was then divided without loss into 21 parts; these were connected by caoutchouc and covered with paraffin.

$$(a) \quad t = 86''$$

$$(b) \quad t = 85'' \quad \text{Mean } 85''\cdot5.$$

These experiments show that the terminations of the tubes exert no special influence on the passage of the current.

A conical or trumpet-shaped tube was then examined, the arrangement being according to fig. 2. The following were the results.

Fig. 2.

Wide end towards greatest pressure.

$$(a) \quad t = 183''$$

$$(b) \quad t = 184'' \quad \text{Mean } 183''\cdot5.$$

Narrow end towards greatest pressure.

$$t = 184''.$$

This shows that the rate is the same both ways.

The foregoing experiments having shown that the effect of temperature on the rate of a current was to be looked for in its influence on fluid-friction, the next thing was to determine the relation between temperature and time, other things being the same. For this purpose a capillary tube, through which a current was passing at a constant pressure, was subjected down its entire length to various temperatures—care being taken that the air should arrive at the entrance of the capillary tube at the temperature of the tube itself, so that the current might be of the same temperature throughout the entire length of the capillary tube. The times of passing of a given quantity of air for different temperatures were noted; and some of the results are subjoined.

I. Pressure 315 millims. of Water.							
Temp. Centigrade. C.	Absolute temp. T.	T ² .	Time. t.	$\frac{T^2}{t}$.	$\Delta\left(\frac{T^2}{t}\right)$.	$\frac{T}{t}$.	$\frac{T(T+94)}{t}$
-20	253	64009	119	538	12	2.42	712
0	273	74529	135.5	550	2	2.27	713
21	294	86436	156.5	552	15	2.13	705
60	333	110889	195.5	567	11	1.88	703
100	373	139129	240.5	578	36	1.65	696
200	473	223729	364.5	614	5	1.37	712
240	513	263169	425	619		1.29	713

II. Pressure 1000 millims. of Water.							
20	293	85849	110	784.5	12.0	2.663	1035
40	313	97969	123	796.5	10.0	2.545	1036
60	333	110889	137.5	806.5	7.9	2.422	1034
80	353	124609	153	814.4	8.8	2.307	1031
100	373	139129	169	823.2	11.6	2.207	1031
120	393	154449	185	834.8	7.9	2.124	1035
140	413	170569	202.4	842.7	3.8	2.040	1034
160	433	187489	221.5	846.5	9.4	1.955	1030
180	453	205209	239.75	855.9	9.6	1.889	1034
200	473	223729	258.5	865.5		1.833	1035
							1033.5

These Tables show—

(1) That the time varies approximately as the square of the absolute temperature. This appears from the approximate equality of the numbers in column 5.

(2) That the variation of the time deviates from the law of squares by a term approximately proportional to the temperature. This is shown by the average equality of the differences in column 6.

(3) That the formula connecting the time and the temperature is very nearly

$$t = dT(T + \beta),$$

where β seems to depend on the pressure $p_1 - p_2$.

From the above series of experiments, however, the exact connexion between β and $p_1 - p_2$ is not obvious; possibly it may be of the form

$$t = \alpha T \left(T + \frac{\beta}{(p_1 + p_2)^3} \right).$$

The next series of experiments had in view the more exact determination of the relation between $p_1 - p_2$ and t .

To obtain these results, it was necessary to determine the effect of capillarity and bubble-tension on the exit of the air through the final orifice.

It was found from experiment that these forces were very nearly equivalent to a pressure of 22 millims. The depth of the exit-orifice under the surface of the water over which the air was collected had, of course, to be allowed for.

The experiments gave the following results:—

Temperature 20° C.

	$p_1 - p_2$.	t .	$(p_1 - p_2) \times t$.	$\Delta(p_1 - p_2)t$.
	millim.			
I. {	+15	3945 ^u	59175	— 4531
	76	719	54644	— 558
	157	344.5	54086	+ 605
	303	180.5	54691	— 826
	513	105	53865	— 729
	656	81	53136	— 518
	852	61.75	52611	— 73
	1205	43.6	52538	
II. {	200	426.5	85300	— 1500
	400	209.5	83800	— 400
	600	139	83400	— 467
	800	103.6	82933	— 933
	1000	82	82000	
III. {	200	563.6	112733	— 1533
	400	278	111200	— 400
	600	184.6	110800	— 934
	800	137.3	109866	— 1866
	1000	108	108000	— 1200
	1200	89	106800	

The approach to equality in the amounts in column 3 shows that the time varies nearly in the inverse ratio of the difference of pressures. The gradual diminution of the number in that column visible, on the whole, shows that this law is slightly deviated from, and that the time diminishes somewhat more rapidly than the reciprocal of the pressure—a conclusion which is at variance with the results arrived at by Bunsen for the passage of gases through porous plugs.