XIV. *On the Thermal Effects of Fluids in Motion. By* William Thomson, *M.A., F.R.S., F.R.S.E., &c., Professor of Natural Philosophy in the University of Glasgow, For. Mem. of the Royal Swedish Academy of Sciences; and* J. P. Joule, *F.R.S., F.C.S., Corr. Mem. R.A. Turin, Vice-President of the Literary and Philosophical Society of Manchester, &c.*

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In a paper communicated to the Royal Society, June 20, 1844, "On the Changes of Temperature produced by the Rarefaction and Condensation of Air*," Mr. Joule pointed out the dynamical cause of the principal phenomena, and described the experiments upon which his conclusions were founded. Subsequently Professor Thomson pointed out that the accordance discovered in that investigation between the work spent and the mechanical equivalent of the heat evolved in the compression of air may be only approximate, and in a paper communicated to the Royal Society of Edinburgh in April 1851, "On a Method of discovering experimentally the relation between the Mechanical Work spent, and the Heat produced by the compression of a Gaseous Fluid†," proposed the method of experimenting adopted in the present investigation, by means of which we have already arrived at partial results‡. This method consists in forcing the compressed elastic fluid through a mass of porous non-conducting material, and observing the consequent change of temperature in the elastic fluid. The porous plug was adopted instead of a single orifice, in order that the work done by the expanding fluid may be immediately spent in friction, without any appreciable portion of it being even temporarily employed to generate ordinary *vis viva*, or being devoted to produce sound. The non-conducting material was chosen to diminish as much as possible all loss of thermal effect by conduction, either from the air on one side to the air on the other side of the plug, or between the plug and the surrounding matter.

A principal object of the researches is to determine the value of μ, Carnot's function. If the gas fulfilled perfectly the laws of compression and expansion ordinarily assumed, we should have§

$$\frac{1}{\mu}=\frac{\frac{1}{E}+t}{J}+\frac{K\delta}{Ep_0u_0\log P},$$

where J is the mechanical equivalent of the thermal unit; p_0u_0 the product of the

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* Philosophical Magazine, S. 3, vol. xxvi. p. 369.

† Transactions of the Royal Society, Edinburgh, vol. xx. Part II.

‡ Philosophical Magazine, S. 4, vol. iv. p. 481.

§ Dynamical Theory of Heat, equation (7), § 80, Transactions of the Royal Society of Edinburgh, vol. xx. p. 297.

pressure in pounds on the square foot into the volume in cubic feet of a pound of the gas at 0° Cent.; P is the ratio of the pressure on the high pressure side to that on the other side of the plug; δ is the observed cooling effect; t the temperature Cent. of the bath, and K the thermal capacity of a pound of the gas under constant pressure equal to that on the low pressure side of the gas. To establish this equation it is only necessary to remark that $K\delta$ is the heat that would have to be added to each pound of the exit stream of air, to bring it to the temperature of the bath, and is the same (according to the general principle of mechanical energy) as would have to be added to it in passing through the plug, to make it leave the plug with its temperature unaltered. We have therefore $K\delta=-H$, in terms of the notation used in the passage referred to.

On the above hypothesis (that the gas fulfils the laws of compression and expansion ordinarily assumed) $\frac{\delta}{\log P}$ would be the same for all values of P; but REGNAULT has shown that the hypothesis is not rigorously true for atmospheric air, and our experiments show that $\frac{\delta}{\log P}$ increases with P. Hence, in reducing the experiments, a correction must be first applied to take into account the deviations, as far as they are known, of the fluid used, from the gaseous laws, and then the value of μ may be determined. The formula by which this is to be done is the following (Dynamical Theory of Heat, equation (f), § 74, or equation (17), § 95, and (8), § 89)—

$$\frac{1}{\mu}=\frac{\frac{1}{J}\{w-(p'u'-pu)\}+K\delta}{\frac{dw}{dt}},$$

where

$$w=\int_u^{u'}pdv,$$

u and u' denoting the volumes of a pound of the gas at the high pressure and low pressure respectively, and at the same temperature (that of the bath), and v the volume of a pound of it at that temperature, when at any intermediate pressure p. An expression for w for any temperature may be derived from an empirical formula for the compressibility of air at that temperature, and between the limits of pressure in the experiment.

The apparatus, which we have been enabled to provide by the assistance of a grant from the Royal Society, consists mainly of a pump, by which air may be forced into a series of tubes acting at once as a receiver of the elastic fluid, and as a means of communicating to it any required temperature; nozles, and plugs of porous material being employed to discharge the air against the bulb of a thermometer.

The pump a, fig. 1, consists of a cast-iron cylinder of 6 inches internal diameter, in which a piston, fig. 2, fitted with spiral metallic packing (of antifriction metal), works by the direct action of the beam of a steam-engine through a stroke of 22 inches. The pump is single-acting, the air entering at the base of the cylinder during the up-stroke, and being expelled thence into the receiving tubes by the down-stroke. The governor of the steam-engine limits the number of complete strokes of the pump to 27 per minute. The valves, fig. 3, consist of loose spheres of brass 0·6 of an inch in diameter, which fall by their own gravity over orifices 0·45 of an inch diameter. The cylinder and valves in connection with it are immersed in water to prevent the wear and tear which might arise from a variable or too elevated temperature.

Fig. 1.

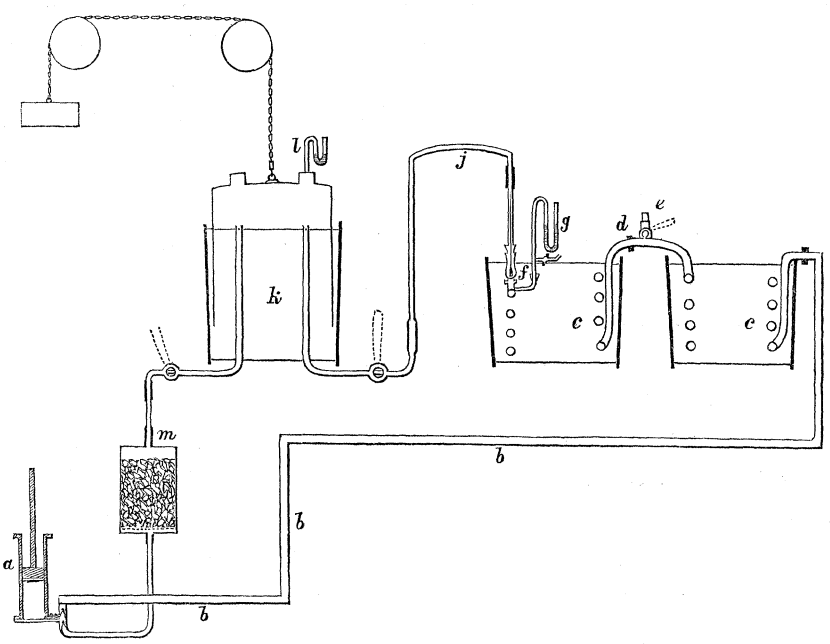


Fig. 2.

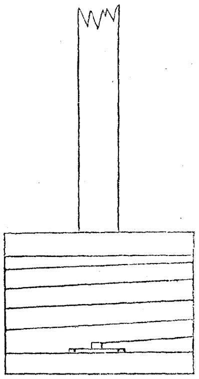


Fig. 3.

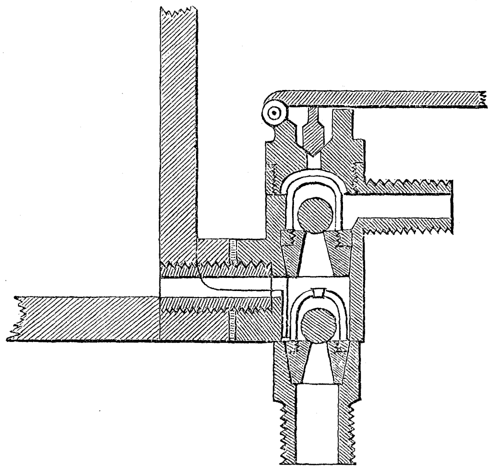
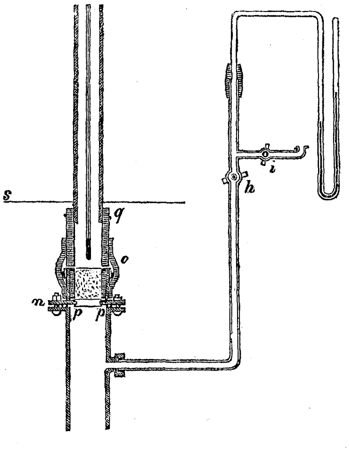


Fig. 4.



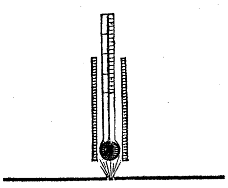
Wrought-iron tubing, *b b*, fig. 1, of 2 inches internal diameter, conducts the compressed air horizontally a distance of 6 feet, thence vertically to an elevation of 18 feet, where another length of 23 feet conveys it to the copper tubing, *c c*; the junction being effected by means of a coupling-joint. The copper tubing, which is of 2 inches internal diameter and 74 feet in length, is arranged in two coils, each being immersed in a wooden vessel of 4 feet diameter, from the bottom and sides of which it is kept at a distance of 6 inches. The coils are connected by means of a coupling joint *d*, near which a stopcock, *e*, is placed, in order to let a portion of air escape when it is wanted to reduce the pressure. The terminal coil has a flange, *f*, to which any required nozle may be attached by means of screw-bolts. Near the flange, a small pipe, *g*, is screwed, at the termination of which a calibrated glass tube bent (as shown in fig. 4), and partly filled with mercury, is tightly secured. A stopcock at *h*, and another in a small branch pipe at *i*, permit the air at any time to be let off, so as to examine the state of the gauge when uninfluenced by any except atmospheric pressure. The branch pipe is also employed in collecting a small portion of air for chemical analysis during each experiment. A pipe, *j*, is so suspended, that by means of india-rubber junctions, a communication can readily be made to convey the air issuing from the nozle into the gas-meter, *k*, which has a capacity of 40 cubic feet, and is carefully graduated by calibration. A bent glass tube, *l*, inserted in the top of the meter, and containing a little water, indicates the slight difference which sometimes exists between the pressure of air in the meter and that of the external atmosphere. When required, a wrought-iron pipe, *m*, 1 inch in diameter, is used to convey the elastic fluid from the meter to the desiccating apparatus, and thence to the pump so as to circulate through the entire apparatus.

We have already pointed out the different thermal effects to be anticipated from the rushing of air from a single narrow orifice. They are *cold*, on the one hand, from the expenditure of heat in labouring force to communicate rapid motion to the air by means of expansion; and *heat*, on the other, in consequence of the *vis viva* of the rushing air being reconverted into heat. The two opposite effects nearly neutralize each other at 2 or 3 inches distance from the orifice, leaving however a slight preponderance of cooling effect; but close to the orifice the variations of temperature are excessive, as will be made manifest by the following experiments.

A thin plate of copper, having a hole of $\frac{1}{20}$th of an inch diameter, drilled in the centre, was bolted to the flange, an india-rubber washer making the joint air-tight. At the ordinary velocity of the pump the orifice was sufficient to discharge the whole quantity of air when its pressure arrived at 124 lbs. on the square inch. When however lower pressures were tried, the stopcock *e* was kept partially open. The thermometer used was one with a spherical bulb 0·15 of an inch in diameter. Holding it as close to the orifice as possible without touching the metal, the following observations were made at various pressures, the temperature of the water in which the coils were immersed being 22° Cent. The air was dried and deprived of carbonic acid by passing it, previous to entering the pump, through a vessel $4\frac{1}{2}$ feet long and 20 inches diameter, filled with quicklime.

Total pressure of the air in lbs. on the square inch.	Temperature Centigrade.	Depression below temperature of bath.
124	8°·58	13°·42
72	11·65	10·35
31	16·25	5·75

Fig. 5.

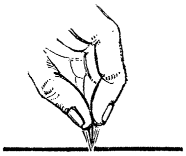


The heating effect was exhibited as follows:—The bulb of the thermometer was inserted into a piece of conical gutta percha pipe in such a manner that an extremely narrow passage was allowed between the interior surface of the pipe and the bulb. Thus armed, the thermometer was held, as represented by fig. 5, at half an inch distance from the orifice, when the following results were obtained:—

Total pressure of the air in lbs. on the square inch.	Temperature Centigrade.	Elevation above temperature of bath.
124	45°·75	23°·75
71	39·23	17·23
31	26·2	4·20

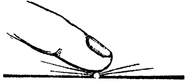
It must be remarked, that the above recorded thermal effects are not to be taken as representing the maximum results to be derived from the rushing air at the pressures named. The determination of these, in the form of experiment above given, is prevented by several circumstances. In particular it must be observed, that the cooling effects must have been reduced in consequence of the heat evolved by the friction of the rushing air against the bulb of the thermometer. The heating effects, resulting as they do from the absorption and conversion into heat of the *vis viva* of the rushing air, depend very much upon the narrowness of the space between the thermometer and gutta percha pipe. We intend further on to return to this subject, but in the mean time will mention three forms of experiment whereby the heating effect is very strikingly and instructively exhibited.

Fig. 6.



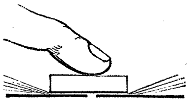
Experiment 1.—The finger and thumb are brought over the orifice, as represented in fig. 6, so that by gradually closing them the stream of air is pinched. It is found that the effort to close the finger and thumb is opposed by considerable force, which increases with the pressure applied. At the same time a strong tremulous motion is felt and a shrill noise is heard, whilst the heat produced in five or six seconds necessitates the termination of the experiment.

Fig. 7.



Experiment 2.—Fig. 7. The finger is placed over the orifice and pressed until a thin stratum of air escapes between the copper-plate and the finger. In this case the burning heat of the rushing air is equally remarkable in spite of the proximity of the finger to the cold metal.

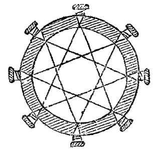
Fig. 8.



Experiment 3.—Fig. 8. A piece of thick india-rubber is pressed by the finger over the narrow orifice so as to allow a thin stream of air to rush between the india-rubber and the plate of copper. In this case the india-rubber is speedily raised to a temperature which prevents its being handled comfortably.

We have now adduced enough to illustrate the immense and sudden changes of temperature which exist in the "rapids" of a current of air, changes which point out the necessity of employing a porous plug, in order that when the air arrives at the thermometer its state may be reduced to a uniform condition. Figs. 4 and 9 represent our first arrangement for the porous plug, where *n* is a brass casting with flange to bolt to the copper tube. It has eight studs, *o*, and eight holes, *pp*, drilled into the inner part of the flange. The studs and holes furnish the means of securing the porous material (in the present instance of cotton wool) in its place, by binding it down tightly with twine. Immediate contact between the cotton and metal is prevented by the insertion of a piece of india-rubber tubing; *qqq* are three pieces of india-rubber tube inserted within each other, the inner one communicating with a glass tube *r*, through which the divisions of the thermometer may be seen, and which serves to convey the air to the meter. In the experiments about to be given, the thermometer was in immediate contact with the cotton plug as represented in the figure, and the nozle was immersed in the bath up to the line *s*. The weight of the cotton wool in a dry state was 251 grs., its specific gravity 1·404, and being compressed into a space $1\frac{1}{2}$ inch in diameter and 1·9 inch long, the opening left for the passage of air must have been equal in volume to a pipe to 1·33 of an inch diameter.

Fig. 9.



First series of experiments. Atmospheric air dried and deprived of carbonic acid by quicklime. Gauge 73·6; barom. 30·04=14·695 lbs. pressure per square inch.

Gauge.		Total pressure in lbs. per square inch.	Cubic inches of air passed per minute reduced to atmospheric pressure.	Temperature of bath* ascertained by Thermometer No. 1, in Centigrade degrees.		Temperature of the issuing air, ascertained by Thermometer No. 2.		Cooling effect.
37·5 37·5 38 37·8	37·7	35·854	12703	445 445·5 445·9 446	445·6 =18°·2676	414 414 414·6 414·8	414·35=17°·8298	0°·4378
38 38 37·8 38	37·9	35·647	12703	446·1 446·6 446·8 447·1	446·65=18·3128	415·4 416 416·8 417·6	416·45=17·9295	0·3833
38 37·75 37·5 37·5	37·69	35·866	12703	447·2 447·5 447·8 448	447·62=18·3545	418 418·2 418·4 418	418·15=18·0110	0·3435

A Liebig tube containing sulphuric acid, specific gravity 1·8, gained 0·03 of a grain by passing through it, during the experiment, 100 cubic inches of air.

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* By varying the temperature of the water in which the coils were immersed, it was found that the temperature of the water surrounding the first coil exercised no perceptible influence, the temperature of the rushing air being entirely regulated by that of the terminal coil. However, the precaution was taken of keeping both coils at nearly the same temperature.

The observations above tabulated were made at intervals of two or three minutes. It will be observed that the cooling effect appeared to be greater at the commencement than at the termination of the series. This may be attributed in a great measure to the drying of the cotton, which was found to contain at least 5 per cent. of moisture after exposure to the atmosphere. There was also another source of interference with the accuracy of the results owing to a considerable oscillation of pressure arising from the action of the pump. We had remarked that when the number of strokes of the engine was suddenly reduced from twenty-seven to twenty-five per minute, a depression of the thermometer equal to some hundredths of a degree Cent. took place, a circumstance evidently owing to the entire mass of air in the coils and cotton plugs suffering dilatation without allowing time for the escape of the consequent thermal effect. Hence it was found absolutely essential to keep the pump working at a perfectly uniform rate. For a similar reason it was also most important to prevent the oscillations of pressure due to the action of the pump, particularly as it appeared obvious that the heat evolved by the sudden increase of pressure, on the admission of a fresh supply of air from the pump, would arrive at the thermometer in a larger proportion than the cold produced by the subsequent gradual dilatation. In fact, on making an experiment in which the air was kept at a low pressure, by opening a stopcock provided for the purpose, the oscillations of pressure amounting to $\frac{1}{20}$th of the whole, it was found that an apparent heating effect, equal to 0°·2 Cent., was produced instead of a small cooling effect.

It became therefore necessary to obviate the above source of error, and the method first employed with that view, was to place a diaphragm of copper with a hole in its centre $\frac{1}{7}$th of an inch in diameter at the junction between the iron and copper pipes. The oscillation being thus reduced, so as to be hardly perceptible, we made the following observations.

Second series of experiments. Atmospheric air dried and deprived of carbonic acid by quicklime. Gauge 73·75; barometer 30·162=14·755 lbs. pressure per square inch; thermometer 19°·3 Cent.

Gauge.		Total pressure in lbs. per square inch.	Cubic inches of air issuing per minute at atmospheric pressure.	Temperature of bath by Thermometer No. 1, degrees Centigrade.		Temperature of issuing air by Thermometer No. 2, degrees Centigrade.		Cooling effect.
39	38·65	36·069	11796	467	467·02=19°·186	434·6	434·9 =18°·810	0°·377
38·6				467		435		
38·5				467		435		
38·5				467·1		435		
38·5	38·79	35·912	11796	467·1	467·2 =19·194	435·1	435·37=18·832	0·362
38·8				467·2		435·4		
38·8				467·2		435·6		
38·75				467·3		435·4		
38·8	38·8	35·900	11796	467·3	467·37=19·202	435·6	435·82=18·854	0·348
38·8				467·4		435·8		
38·8				467·4		435·9		
38·8				467·4		436		

Suspecting that particles of the sperm oil employed for lubricating the pump were carried mechanically to the cotton plug and interfered with the results, we now substituted a box with perforated caps, filled with cotton wool, for the diaphragm used in the last series. With this arrangement the pressure was kept as uniform as with the other, and all solid and liquid particles were kept back by filtration.

Third series of experiments. Atmospheric air dried and deprived of carbonic acid by quicklime*, and filtered through cotton. Gauge 73·7; thermometer 21°·7 Cent.; barometer 30·10=14·71 lbs. on the square inch.

Time of observation.	Gauge.		Total pressure in lbs. per square inch.	Cubic inches of air issuing per minute at atmospheric pressure.	Temperature of bath by Thermometer No. 1, in degrees Centigrade.		Temperature of the issuing air by Thermometer No. 2, in degrees Centigrade.		Cooling effect.
m									
3	39	39·2	34·410	11784	357·7	357·92=14°·506	337·35	337·89=14°·183	0°·323
6	39·1				357·8		337·8		
9	39·5				358		338		
12	39·2				358·2		338·4		
15	39·1	39·19	34·418	11784	358·7	358·97=14·552	338·8	338·85=14·230	0·322
16	39·35				358·9		338·7		
18	39·1				359·1		339		
21	39·2				359·2		338·9		
23	39·2	39·18	34·426	11784	359·4	359·72=14·584	339·25	339·69=14·270	0·314
25	39·1				359·7		339·8		
28	39·2				359·8		339·7		
30	39·2				360		340		
32	39·5	39·34	34·279	11784	360·1	360·27=14·607	340	340·25=14·296	0·311
34	39·3				360·2		340·2		
36	39·25				360·4		340·4		
38	39·3				360·4		340·4		

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* The use of quicklime as a desiccating agent was suggested to us by Mr. Thomas Ransome. It answered its purpose admirably after it had fallen a little by use, so as to be finely subdivided. The perfection of its action was shown by the desiccating cylinder remaining, after having been used two hours, cold at the lower part, while the upper part for about 9 inches was made very hot. The analysis of the air passed during the third series of experiments showed that one of the Liebig tubes had gained no weight whatever; and in one instance we have observed that the sulphuric acid of 1·8 specific gravity, actually lost weight, apparently indicating that the air dried by quicklime was able to remove water from acid of that density.

The stopcock for reducing pressure being now partially opened, the observations were continued as follows:—

Time of observation.	Gauge.		Total pressure in lbs. per square inch.	Temperature of bath by Thermometer No. 1, in degrees Centigrade.		Temperature of the issuing air by Thermometer No. 2, in degrees Centigrade.		Cooling effect.
h m								
50	55·1	55·12	22·876	361·7	362·26=14°·693	344	346·19=14°·579	0°·114
52	55·1			361·9		344·8		
54	55·1			361·9		345·3		
55	55·1			361·9		345·8		
57	55·1			362·1		346·0		
59	55·1			362·3		346·4		
1 1	55·1			362·4		346·9		
3	55·1			362·7		347·2		
5	55·1			362·7		347·6		
7	55·3			363		347·9		
11	54·3	54·51	23·217	363·3	363·82=14·760	348·9	349·74=14·749	0·011
13	54·4			363·3		348·9		
15	54·4			363·5		349·2		
17	54·7			363·7		349·4		
19	54·5			363·9		350		
20	54·5			364·1		350		
22	54·6			364·2		350·3		
24	54·6			364·2		350·4		
26	54·6			364·2		350·6		
30	54·6			375		356·4		
32	54·6			375·4		358·2		
33	54·2	54·38	23·277	375·4	375·7 =15·270	359·4	360 =15·238	0·032
35	54·3			375·5		359·8		
37	54·4			375·8		360		
39	54·6			375·7		360·1		
40	54·3			375·8		360·3		
42	54·5			376		360·4		

During the above experiment 100 cubic inches of the air was slowly passed through two Liebig tubes containing sulphuric acid, specific gravity 1·8. The first tube gained 0·006 of a grain, the second remained at exactly the same weight.

P.S. Oct. 14, 1853.—The apparently anomalous results contained in the last Table have been fully explained, and shown to depend on the alteration of pressure which took place towards the beginning of the interval of time from 42^m to 50^m, by subsequent researches which we hope soon to lay before the Royal Society.