THE VARIATION OF SOUND ABSORPTION COEFFICIENT WITH INTENSITY.

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(*Read January 5, 1937.*)

(Communicated by Prof. M. N. SAHA, D.Sc., F.R.S.)

Section 1. INTRODUCTION.

The variation of sound-absorption coefficient with intensity of sound has never been successfully studied and we have so far failed to find any adequate reference to it in the existing literature. Sabine (1923) using his formula (eqn. 1) for the calculation of the absorbing power of a specimen found that the value of k (eqn. 1) is subject to a correction which varied with the varying experimental circumstances.

$$a' = \frac{kV(t_1' - t_1''')}{t'_1 \, . \, t_1'''} - \frac{SP}{v}\left(\frac{1}{t_1'}\log_e\frac{I_1'}{I} - \frac{1}{t_1'''}\log_e\frac{I_1'''}{I}\right) \quad .. \quad (1)$$

Talking about this he observes : 'The magnitude, as well as the sign of this correction, depends on the intensity of the source of sound, the size of the room and the material of which it is constructed and the area of the windows opened. This is illustrated in the following table (reproduced here in table 1) which is derived from a recalculation of all the rooms in which the open window experiments have been tried and which exhibits a fairly large range in these respects ' (1923).

Substituting Sabine's data (1923) for the first two cases (Table 1) in equation (1) and using the uncorrected value of k in each case, it is possible to

TABLE 1.

Room.	V Cu.	I	W	k Uncorrected.	Correction.	k
1. Lobby Fogg Museum 1 Pipe ..	96	8,800,000	1·86	0·169	0·010	0·159
2. Lobby Fogg Museum 16 Pipes ..	96	67,000,000	1·86	0·191	0·27	0·164
3. Jefferson Physical Laboratory 15 ..	202	1,700,000	5·10	0·164	0·005	0·159
4. Jefferson Physical Laboratory 1 ..	1,630	390,000	12·0	0·150	0·017	0·167
5. Jefferson Physical Laboratory 4 ..	1,960	300,000	14·6	0·137	0·024	0·161

Here W = absorbing power of the open windows, minus their absorbing power when closed.

VOL. IV—No. 3. **[Published October 20th, 1938.**

calculate the amount of change in the absorbing power of the specimen which is due to the variation of the intensity of sound alone. When this is done we find that the absorbing power, a', in these two cases of the Fogg Museum is 2·467 units and 2·951 units when 1 and 16 organ pipes, respectively, were used. From this, it appears that the increase in the intensity of sound from 8,800,000 to 67,000,000 (arbitrary units) has produced an increase in the absorbing power of the substance amounting to about 20%.

Sabine, however, does not seem to have taken into consideration the absorption of sound by the source itself (the organ pipe and its accessories) which does absorb sound, howsoever little. If absorption due to one pipe system be equal to α_1 (same unit) then that due to 16 almost similar organ pipes would be $16\alpha_1$, nearly. Hence, it can be easily seen that by assigning different values to α_1 widely different results are obtained. It is thus clear that due to lack of data regarding α_1 we cannot come to any definite conclusion.

In view of these conflicting results, therefore, the present investigation was undertaken by the author to obtain accurate information regarding the variations in the sound-absorption coefficient due to variations in the intensity of sound. For comparison of these coefficients at different sound intensities the stationary wave method was employed and the various sources of errors inherent in the method were either eliminated or brought well under control so as to obtain reproducible results. The materials so far tested were of the 'yielding' type, such as hair-felt, ordinary thin cloth, cotton-waste and a commercial substance Treetex. A large number of experiments were performed and consistent results were obtained for each specimen. Later on, a few experiments were also performed with a 'non-yielding' type artificial specimen made up of a large number of capillary glass tubes each of 10 cms. length, and of about 1 mm. bore. A discussion of the results is given in the last section.

Section 2. THE THEORY OF THE STATIONARY-WAVE METHOD.

The theory of this method has already been worked out by E. T. Paris (1927) in which he has deduced eqn. (2) to calculate the sound-absorption coefficient of the substance, namely

$$\alpha = \frac{4}{2+\frac{a}{b}+\frac{b}{a}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

where α is the absorption coefficient and $\frac{a}{b}$ is the ratio of the maximum amplitude to the minimum amplitude. Here by 'absorbed sound' is meant that part of the incident sound which is not reflected. To find $\frac{a}{b}$ experimentally we first determine the resistance changes ρ_1 and ρ_2 when the detecting instrument (the hot-wire microphone) inside the pipe is at the minimum pressure-variation and the maximum pressure-variation, respectively; the mouth of the pipe having been stopped by the specimen under test. The specimen is then replaced by a perfect reflector and the positions of the microphone to give the same resistance changes ρ_1 and ρ_2 are determined. Let these positions of the microphone be y_1 cms. and y_2 cms., respectively, distant from the nearest node, the position of which is previously determined. Now, since the pressure amplitude in the stationary wave is proportional to sin ky (y is the distance from the node, $k = \frac{2\pi}{\lambda}$ and λ is the wavelength), the pressure amplitudes producing these resistance changes ρ_1 and ρ_2 must be proportional to sin ky_1 and sin ky_2 so that

$$\frac{a}{b} = \frac{\sin ky_2}{\sin ky_1}$$

from which α is given by

$$\alpha = \frac{4}{2 + \frac{\sin ky_2}{\sin ky_1} + \frac{\sin ky_1}{\sin ky_2}} \qquad \ldots \quad \ldots \quad \ldots \qquad (3)$$

Section 3. APPARATUS.

(*a*) *The experimental pipe.*

The experimental pipe was made up of three pieces of glazed clay pipe of 30 cms. diameter (internal) and in length about 60 cms. each, with a wall-thickness of about 5 cms. These pipes were placed horizontally end to end on padded V-shaped supports, which in turn rested on a raised platform and were cemented together. One of the ends of this composite pipe opened into a wooden box 4′ × 3′ × 3′ which served the purpose of a sound chamber. The specimens to be tested were placed at the other end of the pipe. The specimens had to be cut or shaped in a circular form so as to fit tightly into the circular mouth of the pipe which was lined all along its brim with a washer.

A circular brass-plate of about 0·25 inch in thickness, mounted permanently on a circular wooden disc, 1·5 inches thick and of about 37 cms. in diameter was always used to back the specimen. This whole system, that is the specimen backed with the perfect reflector, could be easily fitted into the mouth of the pipe and kept very rigidly in place by means of a wooden wedge which clamped its central portion as well.

Since the apparatus was kept in a sequestered place in the laboratory, far away from the din of traffic and, further, since most of the experiments were performed during the night or during the quiet part of the day, no other precautions were necessary to avoid extraneous vibrations.

(*b*) *The source of sound.*

The source of sound was a moving-coil-type loud-speaker which was actuated by a valve-maintained tuning-fork oscillator in conjunction with a single-stage valve amplifier. The loud-speaker was kept rigidly fixed inside the sound-chamber and was for all practical purposes fully insulated from extraneous influences.

(c) *Intensity of sound.*

To measure the intensity of sound, the oscillatory current in the primary of the loud speaker transformer was first rectified by means of a full-wave rectifier, namely a copper-oxide metal rectifier (range 1m. amp.) and then passed through a sensitive galvanometer which was shunted to bring the deflection within range. The deflection (I_R) of this galvanometer was then taken to indicate the valve of sound-intensity in terms of arbitrary units, for a given value of the current (I_m) in the field-coil of the loud-speaker. The current in the field-coil was measured by a low-resistance milli-voltmeter (in the absence of a suitable milli-ammeter). Thus the intensity of sound is ultimately read by a combination of (I_R) and (I_m) and hence any change in the value of (I_m) will mean a different intensity of sound though (I_R) may read the same.

The variations in the sound-intensity, as measured in terms of $(I_R \,;\, I_m)$, were effected by altering the values of (I_R) and keeping (I_m) constant. Alterations in the values of (I_R) could be brought about by altering (1) the filament current of the amplifier valve or (2) the plate-voltages of the amplifier and the oscillator valves.

By keeping the plate and the filament voltages of these valves steady and also the current (I_m), it was possible to maintain any desired intensity of sound constant to about 0·2% of itself.

To roughly estimate in decibels the order of sound intensity, the tuning fork method of Davis (1930) was employed and it was found that the intensity of sound $(I_R = 20 \,;\, I_m = 75)$ corresponded to about 25 decibels and that of sound $(I_R = 120 \,;\, I_m = 75)$ corresponded to about 55 decibels so that the range of sound-intensity employed in the present investigation was roughly from 25 to 55 d.b. Since we had no better arrangement to find out the intensity values in decibels we have thought it best to give these relative values of the sound-intensity in the arbitrary units $(I_R \,;\, I_m)$.

The frequency of the loud-speaker note was fairly constant as it was fed by a valve-maintained tuning-fork oscillator of frequency about 511. It may, however, be remarked that the frequency of this note varied to an extent (maximum) of about 7 parts in 10,000 as we changed the intensity from its lowest value to the maximum one. This was due to the use of iron pole-pieces in the oscillator. These changes in frequency were measured by counting beats by another standard tuning fork of frequency 512 cycles per second.

(d) *Hot-wire microphone.*

The measurements of the ratio of maximum to minimum velocity amplitude inside the pipe were carried out by means of a selective hot-wire microphone of small dimensions similar to the one used by Tucker (1921, 1927),

E. T. Paris and others. The (safe) current carrying capacity of the microphone grid was about 40 milli-amperes ; but it was heated by a steady current (I_g) never exceeding about 32 milli-amperes. The value of (I_g) was purposely kept low to avoid excessive heating of the grid which might give rise to evaporation effect (1914).

The microphone as a whole was rigidly supported at the end of a long rod and so arranged that its orifice always lay on the axis of the pipe for all to and fro movements of the rod and that there was no danger of tilting it during its movements inside the pipe.

By moving the rod from outside, the position of the microphone inside the pipe could be varied as desired. The finer movements of the microphone were controlled by a rack and pinion arrangement. The positions of the microphone inside the pipe could be measured from outside by a comparator method using a travelling microscope reading up to 0·01 cm.

The resistance changes due to the cooling of the microphone grid by sound in the pipe were measured by means of a sensitive bridge shown in Fig. 1 up to 0·1 ohm from the (dial-type) resistance box D and to 0·001 ohm. in terms of the deflection of the galvanometer G_m, the sensitivity of which was about 10^{-8} amp. per mm. deflection at a distance of one metre.

A similar hot-wire microphone which was mistuned and shielded from all kinds of noises was also included in the bridge-circuit outside the pipe. The mistuning and shielding of the dummy microphone was a necessary precaution to avoid all stray noises, as well as the note from the loud-speaker. Later on the dummy microphone was altogether removed with advantage. A full diagram of the electrical connections is given in Figs. 1, 2 and 3.

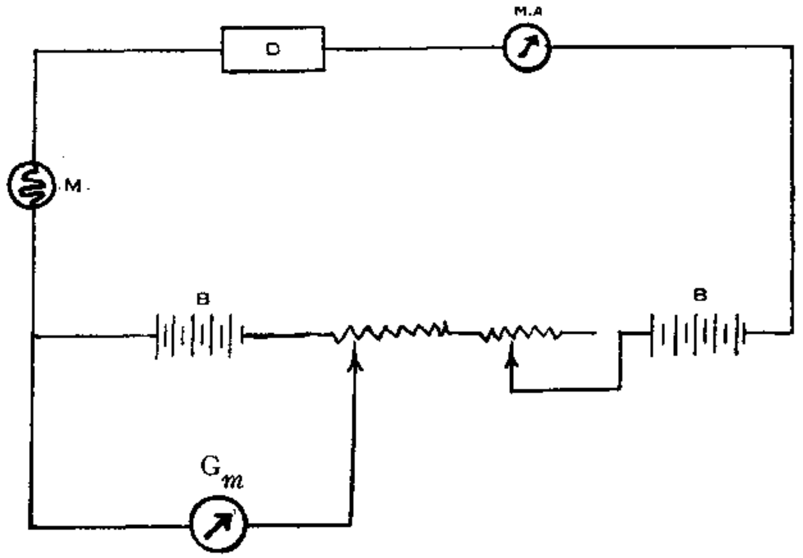

FIG. 1.

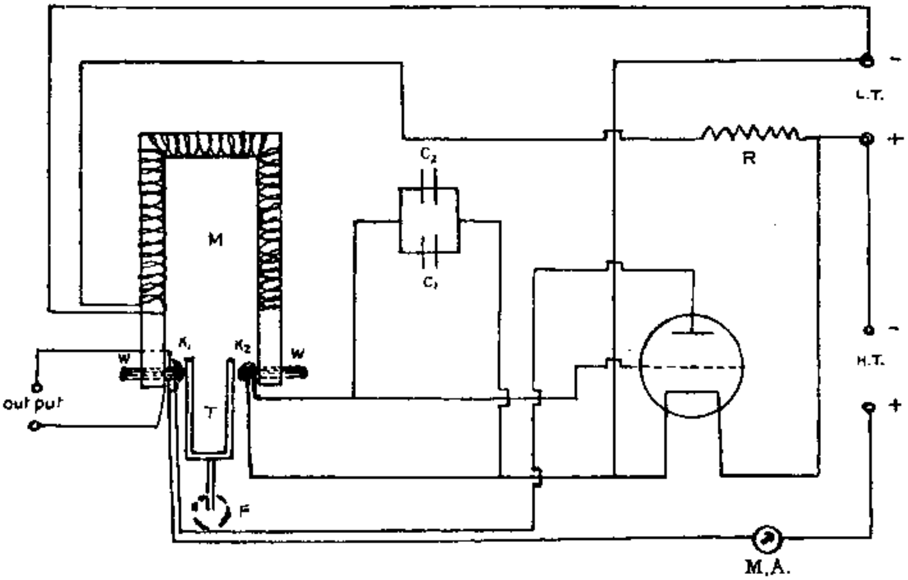

Fig. 2.

Circuit diagram of oscillator.

R—A small wire resistance.

M.A.—Milliammeter.

W—Pole pieces made of a bundle of wires.

T—Tuning fork.

M—Electromagnet.

C_1 & C_2—Condensers.

F—Base where the tuning fork was fixed.

k_1, k_2—Coils wound over wooden reels.

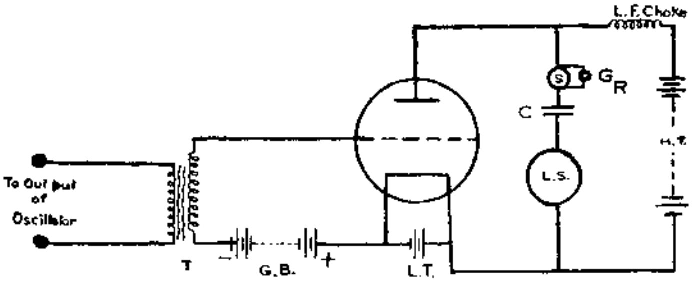

Fig. 3.

Circuit diagram of amplifier.

T—Input transformer.

C—Condenser.

G_R—M.C. Dead beat mirror galvanometer

G.B.—Grid Bias battery.

L.S.—M.C. Loud speaker.

S—Copper oxide Metal Rectifier.

Section 4. METHOD OF OBSERVATION.

After tuning the hot-wire microphone in the usual way the open end of the experimental pipe was carefully closed by the specimen and allowed to remain there undisturbed till all the readings for various sound intensities were completed. This procedure was adopted in order to avoid variations in the absorption coefficient due to direct leakage of sound. Hence any absorption of sound which might be due to its direct leakage under a particular mode of closing the pipe remained constant for all the various intensities used. For a similar reason the sound chamber also was not disturbed after having been once closed. Then the current in the hot-wire grid was adjusted to some suitable value (I_g) and the steady balance point (i.e. without sound) of the spot of light from the galvanometer, G_m, was obtained. The source of sound was switched on and for a given value of the intensity, the readings for ρ_1 and ρ_2 being obtained in the following manner.

The microphone was slowly shifted until it indicated a change of resistance ρ_1 which was minimum. The correct* position of the microphone corresponding to ρ_1, thus obtained, was noted down on the travelling microscope. The microphone was then kept fixed at this correct position and several readings to obtain ρ_1 were taken. The average of these readings was considered to be the most probable value of ρ_1 for that particular value of the intensity of sound.

Exactly in the same manner, the position of the microphone was located at the neighbouring loop and the average value of ρ_2 (ohms), the maximum change in its resistance, due to sound of the same intensity, as before, was obtained.

The procedure was repeated for different values of sound-intensity and the positions of maxima, minima and the values of ρ_1 and ρ_2 were determined in each case separately.

Determination of y_1 and y_2.

To determine the values of y_1 and y_2 the specimen was removed from the mouth of the pipe and the perfect reflector alone was carefully fitted and the

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* To obtain a correct value for the minimum position the microphone was slightly displaced from its minimum position until the resistence change became ρ_1', ($\rho_1' > \rho_1$) and the corresponding position of the microphone was noted. The microphone was displaced slightly further, again in the same direction, until the resistance change became ρ_1'', ($\rho_1'' > \rho' > \rho_1$) and the position of the microphone corresponding to ρ_1'' was also noted. Let these positions of the microphone corresponding to resistance changes ρ_1, ρ_1' and ρ_1'' be x_1, x_1' and x_1'', respectively. Further, the positions of the microphone corresponding to the same resistance changes ρ_1' and ρ_1'', but on the opposite side of its minimum, were also located in the same manner by displacing the microphone in the reverse direction. Let the positions of the microphone now be x' and x'', respectively. The correct position of the microphone for the minimum resistance change was then taken as an average of the readings, namely,

$$(1)\ x_1;\quad (2)\ \tfrac{1}{2}(x_1' - x')\ \text{and}\ (3)\ \tfrac{1}{2}(x_1'' - x'').$$

position of the microphone, when it was located at a node, was noted down on the microscope, as previously done. The microphone was then displaced from this nodal point to such an extent that the resistance change was ρ_1, the same as was obtained in the specimen-experiment for the same intensity of sound. The value of this displacement y_1 cms. from the nodal point was then accurately measured on the microscope. By repeating this to obtain the position of the microphone, on the opposite side of the nodal point, for the same resistance change, the value of $2y_1$ cms. was also obtained.

Similarly, the value of the displacement y_2 cms. of the microphone from the node, required to produce the resistance change ρ_2 for the same intensity, was also obtained.

And in this manner the values of y_1 and y_2 were successively determined for all the intensities that were employed in the series of ρ_1 and ρ_2 determinations in the specimen-experiment without, of course, disturbing that particular mode of closing the pipe or the sound-chamber.

Finally, by measuring distances between the successive minima, the wavelength λ could be determined and the value of k $\left(k = \frac{2\pi}{\lambda}\right)$ calculated ; and using this value of k in eqn. (3) the value of α for each sound-intensity could be obtained.

Section 5. EXPERIMENTS.

In this section a description of the various experiments performed with the different substances, already mentioned, is briefly given and for a few typical cases the actual readings obtained during the experiment are also presented in tabular forms.

I.

Cotton-waste

The cotton-waste specimen was made by loosely packing cotton-waste into a circular wooden frame-work of the required diameter which fitted tightly into the mouth of the experimental pipe. The average depth of cotton-waste was found to be about 2 inches. An open-meshed wire gauze was also stretched across its exposed end to prevent the cotton-waste from slipping or becoming more loose during the progress of any particular experiment. This precaution was necessary for obvious reasons and it enabled us to make such a specimen retain its absorptive properties constant at least for each complete experiment, during which it was never disturbed. The specimen was backed with the perfect reflector. The readings for two different experiments with the same specimen are set down in Tables 2 and 3 and the results are plotted in Figs. 4 and 5 respectively.

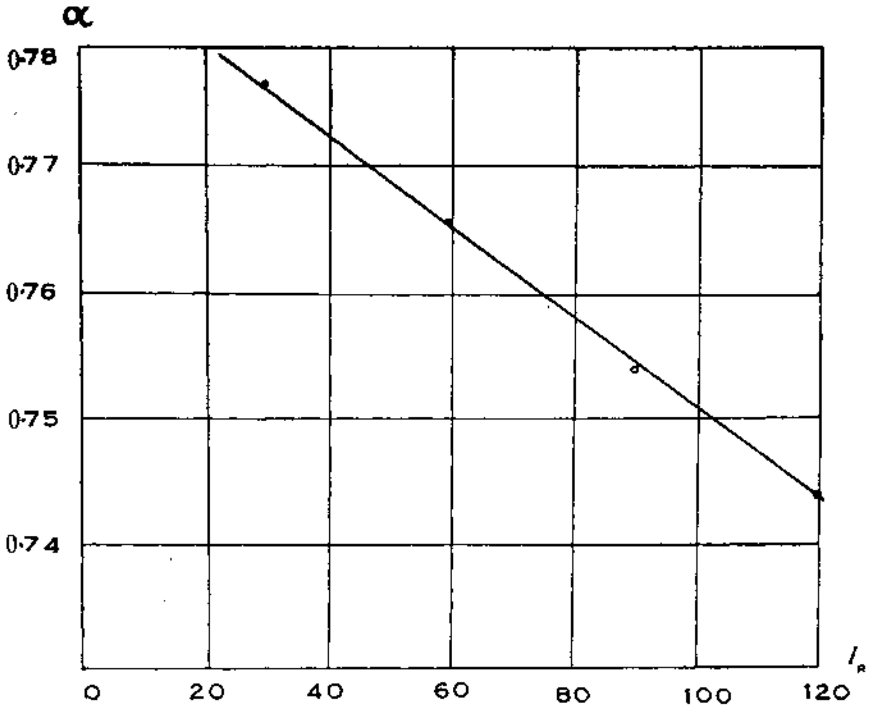
α
0·78
0·77
0·76
0·75
0·74
0
20
40
60
80
100
120
l_s

Fig. 4.

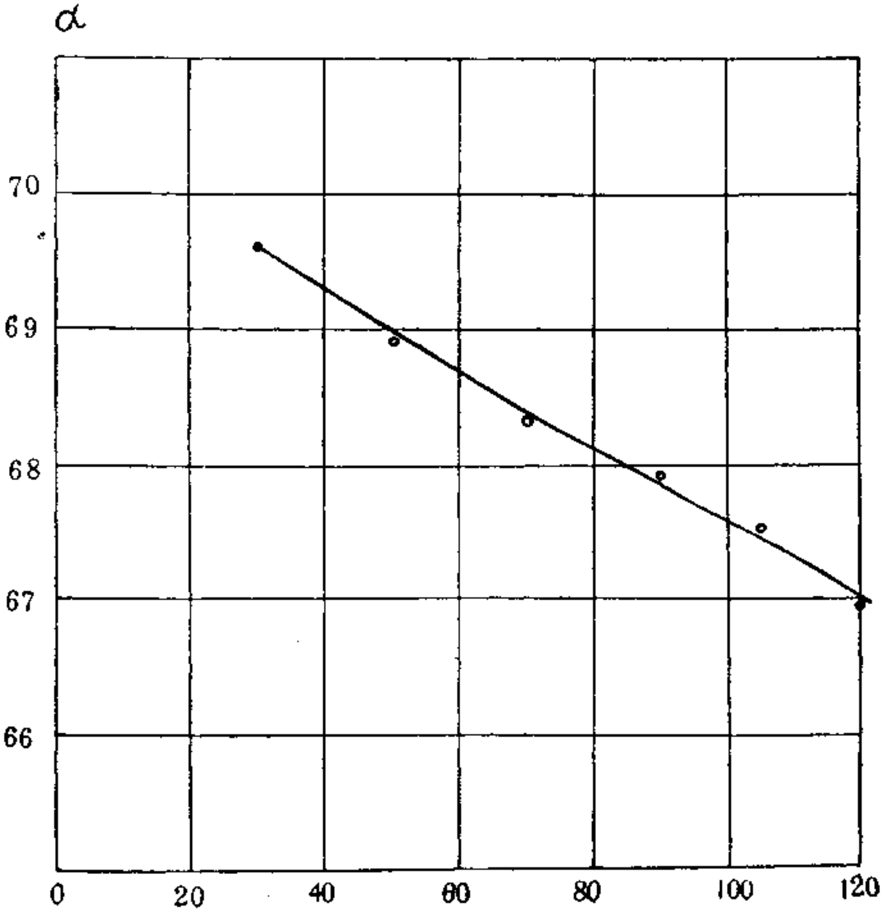
α
70
69
68
67
66
0
20
40
60
80
100
120

Fig. 5.

TABLE 2.

Specimen: Cotton-waste, 2 inches thick. $k = 0·091$

	I_g m. amps	I_m Div.	I_R	ρ_1	ρ_2	y_1	y_2	
1	28·8	75·0	30·0	40·5 mm.	1·3 ohm + 30 mm.	2·40 cm.	7·11 cm.	0·777
2	28·8	75·0	60·0	0·3 ohm. + 9 mm.	5·8 ohm. − 10 mm.	2·37 cm.	7·28 cm.	0·766
3	28·8	75·0	90·0	0·7 ohm. + 13 mm.	12·4 ohm. + 35 mm.	2·32 cm.	7·39 cm.	0·754
4	28·8	75·0	120·0	1·4 ohm. + 11 mm.	18·4 ohm. − 10 mm.	2·28 cm.	7·48 cm.	0·744

TABLE 3.

Specimen: Cotton-waste, 2 inches thick. $k = 0·090$

	I_g m. amps.	I_m Div.	I_R Deflexion.	ρ_1	ρ_2	y_1 cms.	y_2 cms.	
1	32·1	75·0	30·0	39·0 mm.	0·7 ohm. − 10 mm.	2·730	11·05	0·696
2	32·1	75·0	50·0	104·0 mm.	2·3 ohm. + 20 mm.	2·680	11·10	0·689
3	32·1	75·0	70·0	0·2 ohm. + 33 mm.	5·4 ohm.	2·650	11·22	0·683
4	32·1	75·0	90·0	0·4 ohm. + 6 mm.	10·8 ohm.	2·640	11·35	0·678
5	32·1	75·0	105·0	0·5 ohm. + 54 mm.	15·9 ohm.	2·635	11·50	0·675
6	32·1	75·0	120·0	0·8 ohm. − 20 mm.	21·4 ohm.	2·620	11·65	0·669

II.

Treetex

The next substance under test was Treetex—a fibrous substance of fairly high absorbing properties. The average thickness of the substance is about 0·6 inch and, according to the manufacturers, the value of its sound-absorption coefficient is approximately 30%. Three pieces were cut from a sheet of Treetex and joined together so as to form a disc of the required size (37 cms. diameter). It was then mounted on the perfect reflector as usual. The cutting into pieces and then joining into a disc was purposely done to get the joints and to discourage vibration (if any) as a whole, of the specimen. Table 4 contains the readings of the experiment with Treetex, the result is shown in Fig. 6.

TABLE 4.

Specimen: Treetex about 0·6 inch thick. $k = 0·092$

	I_G m. amps.	I_m Div.	I_R Deflexion.	ρ_1	ρ_2	y_1	y_2	α
1	29·2	75·0	30·0	14·0 mm.	2·10 ohm.	1·05 cm.	13·22 cm.	0·338
2	29·2	75·0	60·0	55·0 mm.	8·65 ohm.	1·03 cm.	13·50 cm.	0·331
3	29·2	75·0	75·0	0·1 ohm. + 18 mm.	12·55 ohm.	1·00 cm.	13·75 cm.	0·321
4	29·2	75·0	90·0	0·2 ohm. − 16 mm.	16·25 ohm.	0·92 cm.	13·80 cm.	0·299
5	29·2	75·0	100·0	0·2 ohm. + 14 mm.	18·20 ohm.	0·955 cm.	13·40 cm.	0·311
6	29·2	75·0	120·0	0·3 ohm. + 12 mm.	22·55 ohm.	0·975 cm.	13·20 cm.	0·319

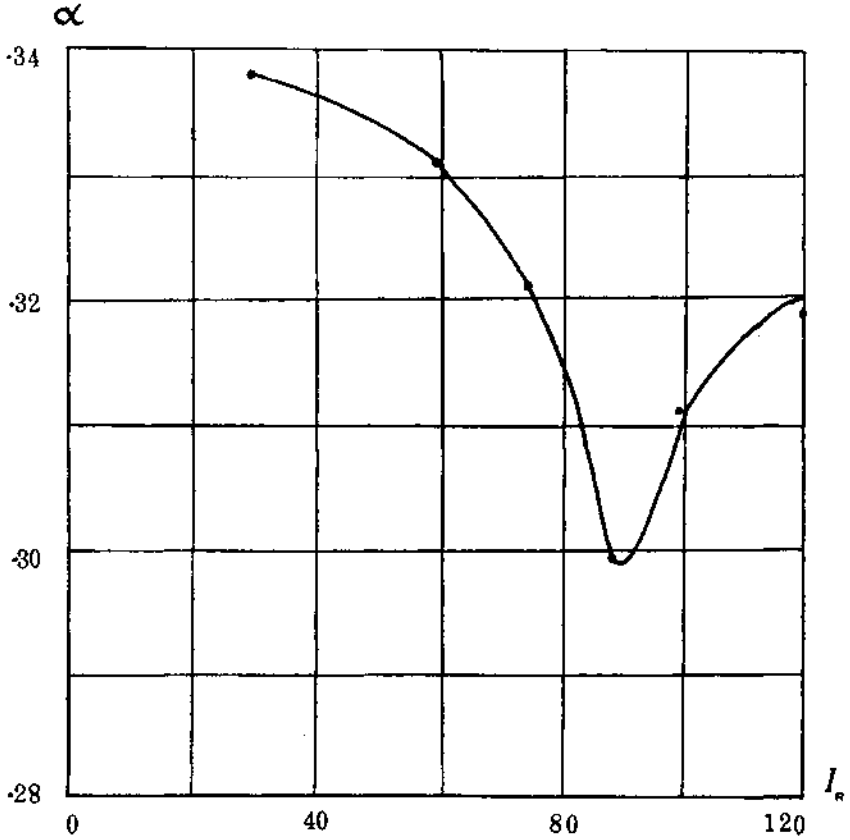

FIG. 6.

III.

Hair-felt.

The third substance tested was coarse hair-felt about 0·4 inch thick. It was cut into a circular form and mounted on the perfect reflector in such a manner that there was no space left between the felt and the perfect reflector. The data for an experiment with this substance are set down in Table 5 and the result plotted in Fig. 7. A different piece of hair-felt, fresh from the market

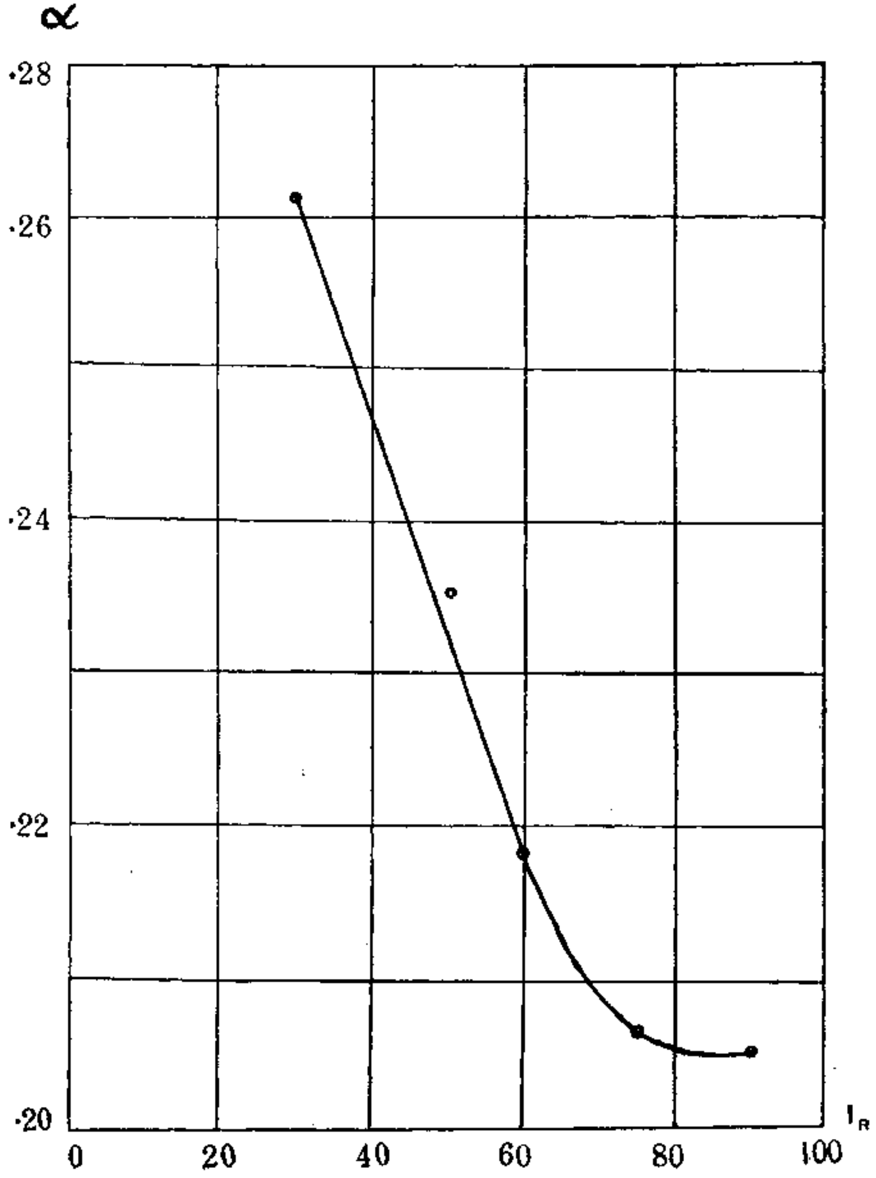

FIG. 7.

and about 0·5 inch thick, was also tested. The typical readings for this specimen are shown in Table 6 and the result plotted in Fig. 8.

TABLE 5.

Specimen: Hair-felt about 0·4 inch thick. $k = 0{\cdot}90$

	I_G m. amps.	I_m Div.	I_R Deflexion.	ρ_1	ρ_2	y_1	y_2	α
1	27·8	65·0	30·0	1·0 mm.	0·86 ohm.	0·70 cm.	11·00 cm.	0·261
2	27·8	65·0	50·0	2·5 mm.	2·70 ohm.	0·63 cm.	11·20 cm.	0·235
3	27·8	65·0	60·0	3·0 mm.	3·80 ohm.	0·58 cm.	11·30 cm.	0·218
4	27·8	65·0	75·0	5·0 mm.	6·70 ohm.	0·55 cm.	11·45 cm.	0·206
5	27·8	65·0	90·0	7·0 mm.	9·50 ohm.	0·55 cm.	11·55 cm.	0·205

TABLE 6.

Specimen: Hair felt 0·6 inch thick. $k = 0{\cdot}09$

	I_G m. amps.	I_m Div.	I_R Deflexion. mms.	ρ_1	ρ_2	y_1 cms.	y_2 cms.	α
1	32·5	75·0	20·0	4·5 mm.	1·3 ohm.	0·900	12·30	0·304
2	32·5	75·0	30·0	8·0 mm.	2·10 ohm.	0·895	12·65	0·299
3	32·5	75·0	40·0	11·5 mm.	2·85 ohm.	0·895	12·80	0·298
4	32·5	75·0	60·0	18·5 mm.	5·2 ohm.	0·880	13·05	0·292
5	32·5	75·0	80·0	27·5 mm.	7·8 ohm.	0·875	13·10	0·290
6	32·5	75·0	100·0	40·0 mm.	10·15 ohm.	0·875	13·14	0·289
7	32·5	75·0	120·0	52·5 mm.	13·4 ohm.	0·855	13·19	0·283
8	32·5	75·0	140·0	64·0 mm.	17·3 ohm.	0·810	13·33	0·269
9	32·5	75·0	150·0	68·5 mm.	19·1 ohm.	0·815	13·25	0·271
10	32·5	75·0	160·0	73·0 mm.	20·9 ohm.	0·815	13·20	0·272
11	32·5	75·0	180·0	94·5 mm.	23·1 ohm.	0·885	13·10	0·292
12	32·5	75·0	190·0	106·0 mm.	24·1 ohm.	0·895	13·00	0·296

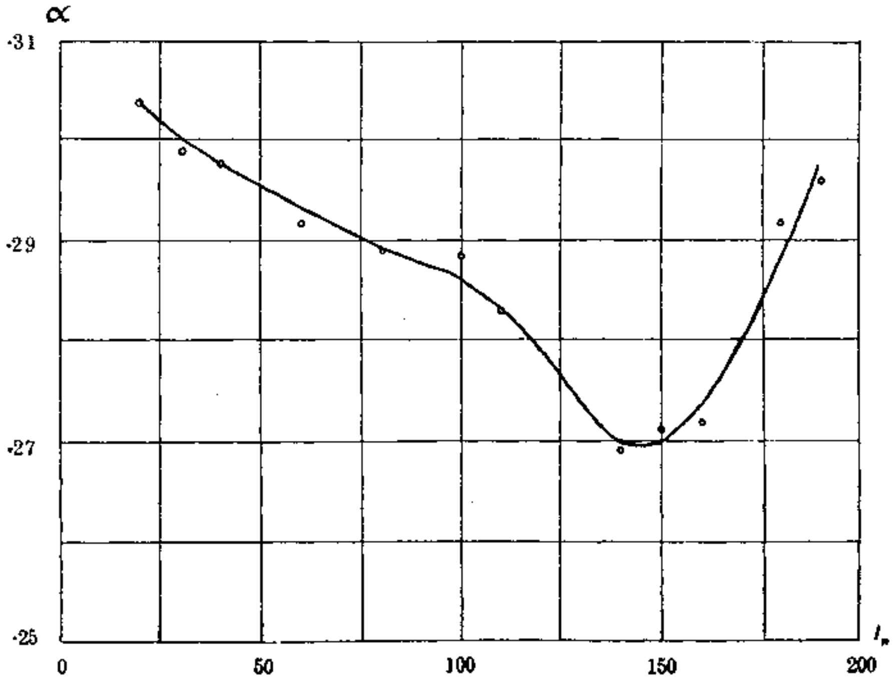

FIG. 8.

IV.

Tool.

The fourth substance tried was ‘ Tool ’ (Hindustani name for a kind of thin red cloth of coarse texture). It was mounted on the perfect reflector. The readings for this substance are set down in Table 7 and the result plotted in Fig. 9.

TABLE 7.

Specimen: Tool, single layer about 0·5 mm. thick. $k=0{\cdot}089$

	I_G m. amp.	I_m Div.	I_R Deflexion.	ρ_1	ρ_2	y_1 cm.	y_2 cms.	α
1	28·8	70	50	7·5 mm.	7·95 ohm.	0·300	14·48	0·105
2	28·8	70	82	24·0 mm.	18·53 ohm.	0·285	14·48	0·100
3	28·8	70	110	43·0 mm.	26·67 ohm.	0·280	14·52	0·098

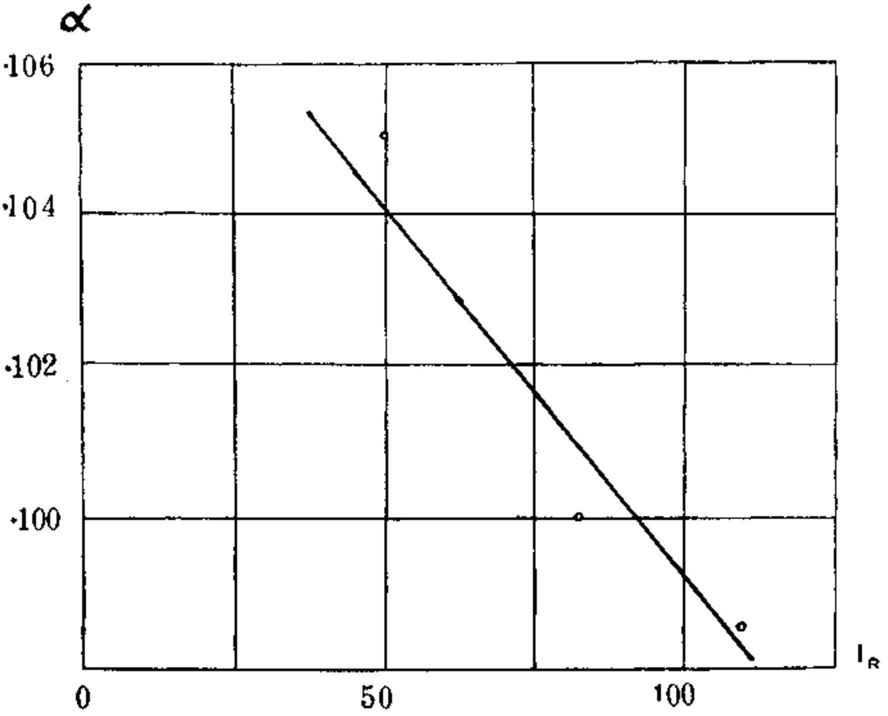

FIG. 9.

V.

Capillary-tube-specimen.

This artificial specimen was made by arranging perpendicularly a large number of thin capillary tubes in a cylindrical vessel whose diameter was about 15 cms. and height about 11 cms. The length of each capillary tube (vaccine tube) was 10 cms. and its average bore was estimated to be about 0·1 cm. by measuring the bores of a few typical tubes of the lot. The average thickness of the wall of the tube was of the order of 0·02 cm. The number of tubes required to fill this vessel completely was about 9,000. This specimen had mostly two types of capillary channels depicted in Fig. 10 by (*a*) and (*b*). The number of (*b*) type channels in the honey-comb structure of the specimen was estimated to be about the same as that of the (*a*) type channels, i.e., 9,000. The cross-sectional area of the total (*b*) type channels was about 8% to 10%

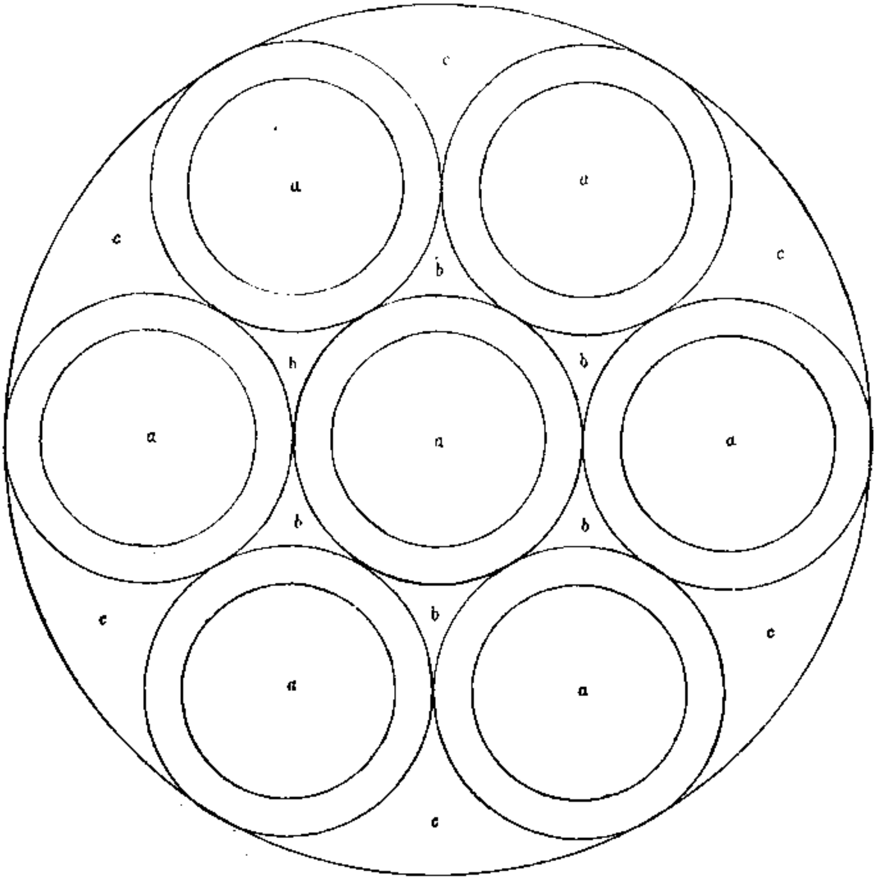

FIG. 10.

of the cross-sectonal area of the total (*a*) type channels. Further, the dimensions of the specimen and the density of glass being known, the total area of perforation was calculated to be 98 sq. cms. approximately. Hence, the ratio of the perforation to the total area was equal to 0·55.

In performing experiments with the above specimen, the experimental pipe (internal diameter 30 cms.) was replaced by a smaller pipe of internal diameter 15 cms. and of length 180 cms. The specimen, described above, could be easily placed tightly inside the mouth of the experimental pipe and backed with a heavy perfect reflector, which consisted of a brass plate 0·25 thick permanently mounted on a wooden disc ($1\frac{1}{2}''$ thick) and of diameter about 20 cms.

The readings for the experiment performed with this specimen are set down in Table 8 and the result plotted in Fig. 11.

TABLE 8.

Specimen: Capillary glass-tube assemblage. $k = 0·09$

	I_G m. amp.	I_m Div.	I_R Deflexion, mms.	ρ_1	ρ_2	y_1	y_2	α
1	28·1	70·0	30	0·1 ohm. + 15 mm.	6·0 ohm. + 25 mm.	2·34 cm.	11·62 cm.	0·627
2	28·1	70·0	60	0·2 ohm. + 18 mm.	11·6 ohm.	2·34 cm.	11·73 cm.	0·625
3	28·1	70·0	100	0·4 ohm. + 35 mm.	19·3 ohm.	2·32 cm.	11·80 cm.	0·620
4	28·1	70·0	150	0·8 ohm. − 15 mm.	27·7 ohm.	2·32 cm.	12·04 cm.	0·616
5	28·1	70·0	200	1·3 ohm. + 5 mm.	31·5 ohm.	2·32 cm.	12·40 cm.	0·610
6	28·1	70·0	230	1·8 ohm. + 10 mm.	35·6 ohm.	2·31 cm.	12·60 cm.	0·605
7	28·1	70·0	270	2·8 ohm. − 5 mm.	38·3 ohm.	2·31 cm.	12·82 cm.	0·601

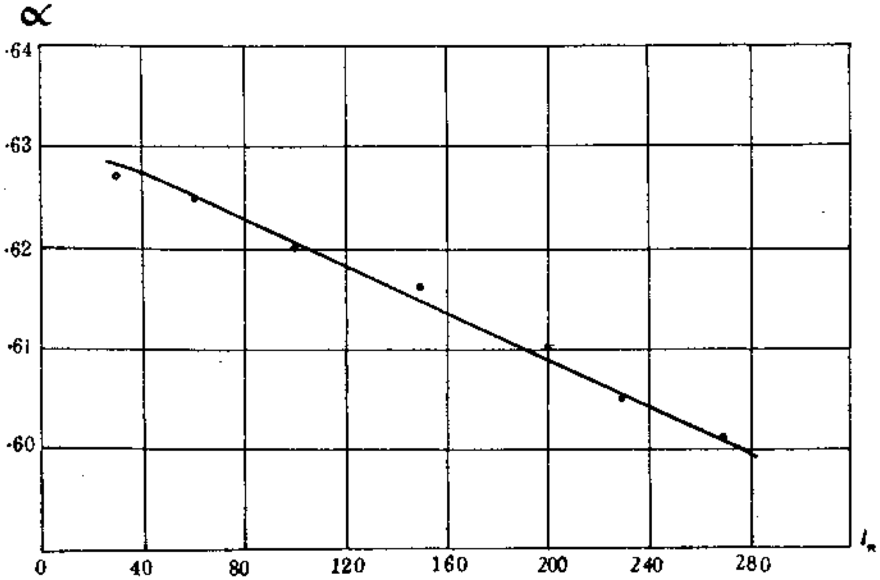

FIG. 11.

Section 6. RESULTS.

In this section the results of experiments are presented separately for each specimen tested and a general discussion of the same is also appended.

1. *Cotton-waste.*

From Tables 2 and 3, and Figs. 4 and 5, it may be readily seen that an increase in the intensity of sound incident normally upon the above specimen produces a marked decrease in its absorption coefficient and that this decrease is almost a linear one. By taking an aggregate of several results, it is found that a change in the intensity of sound from 25 d.b. to about 55 d.b causes a decrease in α of the order of 4 to 5% of itself.

2. *Treetex.*

It is interesting to note that the curve (Fig. 6) depicting the variation of the absorption coefficient of Treetex with intensity indicates a minimum value of the same. Increase in the intensity of sound from 25 d.b. upwards is found to produce, at first, a continuous decrease in α up to about 40 d.b. and for further increments up to 55 d.b. α is found to increase continuously. The maximum decrease in α was of the order of 10% of its value corresponding to the intensity of about 25 d.b.

3. *Hair-felt.*

The α-intensity curves (Figs. 7 and 8) for the two different samples of this substance also show a minimum value of α corresponding to an intensity somewhere between 45 d.b. and 50 d.b. This decrease in α at the minimum is of the order of 25% of its value corresponding to 25 d.b.

4. *Tool.*

The α-intensity curve (Fig. 9) obtained for this substance shows a linear decrease of α which is of the order of 7% of itself for a change of intensity from 25 d.b. to 45 d.b. The variation of α for this substance is more or less similar to that obtained for cotton-waste.

5. *The glass-tube specimen.*

The absorption coefficient of this artificial substance is found to decrease with intensity (almost linearly) in a manner depicted by the curve shown in Fig. 11. The decrease in α is between 6% to 7% of its value for a change of intensity from 25 d.b. to about 60 d.b.

From the results given above it may be gathered that in the case of the felted substances, so far tested, the value of absorption coefficient, at first, decreases with the intensity of sound until it reaches a minimum value, after which it begins to increase with further increase in the intensity. Whereas in all other cases α is always found to decrease with the intensity of sound up to about 60 d.b., the highest intensity employed in the test. Whether for still higher intensities these substances will also have a minimum value of α is a matter that requires further investigation.

Section 7. DISCUSSION OF RESULTS.

The ' perfect ' reflector which was used in these experiments never fulfilled the condition of the ideal reflector demanded by the theory of the method (§2) and so the waves inside the pipe were not perfectly stationary. From the deflection of the galvanometer, obtained at a nodal point in such a stationary wave-system, the absorption*-coefficient of the reflector was calculated to be of the order of 0·015 and, hence, its reflection coefficient was only 98·5%, approximately, instead of 100% required by the theory. From the practical point of view, however, this slight defect of the reflector could be safely ignored; and also since it remained constant for all the intensities used it could not vitiate the observed results.

The perfect reflector being very thick and heavy there could have been little chance of its vibration under the pressure of waves (frequency 511), especially when its central portion was also rigidly clamped by the wooden-wedge (§3). This was proved by the fact that the nodal point in the stationary wave pattern, when the perfect reflector alone was used, did not indicate any shift in their position with variations in the sound intensity. Consequently, there was no possibility of the specimen (backed by the perfect reflector) behaving like a light panel and changing its transmittance with variations in the intensity of sound incident upon it. The employment (in the test) of every inelastic substance, like cotton-waste, is also an assurance that the observed variations in the absorption coefficient with intensity were free from this error.

It may be recalled that the maximum variation in the frequency of the note employed in the test was of the order of about 7 parts in 10,000 and this must have slightly decreased the sensitivity of the tuned hot-wire microphone. This factor, however, cannot affect the value of α because at any particular intensity (hence frequency) the microphone has absolutely the same sensitivity while taking readings for ρ_1 and ρ_2 as that for y_1 and y_2. The variations in α due to slight changes in the frequency of the note, in the present case, are negligible ; in fact, for hair-felt half an inch thick, this can be shown, from the already existing data (1936), to be of the order of 0·0001 ; and in cases other than hair-felt it is still smaller.

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* This includes all energy losses due to leakage, transmission, etc. of sound from the end of the pipe in which the reflector is tightly fitted.

The oscillogram of the oscillatory current from the tuning-fork oscillator (Fig. 12) shows that the current which actuated the speaker was not sinusoidal. But the components present were remote from 512 and so they could not have influenced the detecting instrument which was highly selective in character and tuned to a frequency of 511 cycles per second.

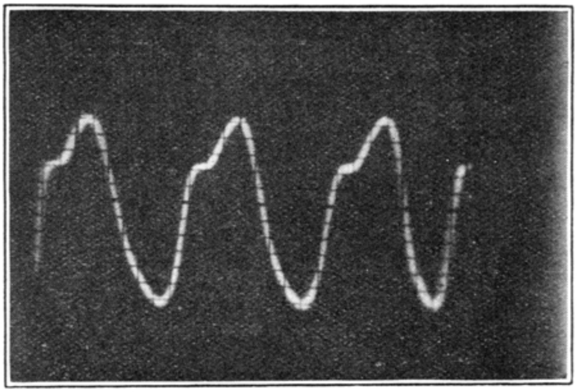

FIG. 12.

Finally, to be more certain of the observed results the experiments were repeated by replacing (1) the hot-wire microphone by another of similar design and make, and (2) the full-wave rectifier by another rectifier and later on by a suitable vacuum thermocouple. The experimental pipe and the sound-chamber were also replaced and under all circumstances the same type of results were obtained.

Section 8. A POSSIBLE EXPLANATION OF THE OBSERVED DECREASE IN THE VALUES OF THE ABSORPTION COEFFICIENT WITH INCREASE OF INTENSITY OF SOUND.

The results given in section (6) indicate a decrease of absorption coefficients of various substances. In the case of hair-felt and Treetex the decrease is as much as 25 and 10%, respectively, while in the case of cotton-waste and vaccine tubes the decrease is much less, viz. 5 and 7%, respectively. Now, a decrease in the value of the absorption coefficient means an increase in the value of the reflection coefficient

$$\dot{\xi}_r / \dot{\xi}_i$$

given by

$$\frac{\dot{\xi}_r}{\dot{\xi}_i} = \frac{\rho'c'/\rho c - 1}{\rho'c'/\rho c + 1} \quad \cdot\cdot \quad \cdot\cdot \quad \cdot\cdot \quad \cdot\cdot \quad (4)$$

where $\frac{\rho' c'}{\rho c}$ represents the ratio of the acoustic impedances of two media. If the reflection occurs at the surface of a porous material, then this ratio is given by

$$\frac{\rho' c'}{\rho c} = 1 + (1-i)\frac{\Delta}{4\pi} \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

where the porous material is considered to be an assemblage of a large number of fine tubes of radius 'a' and Δ is the thickness of the laminar shell which is discussed in the following paragraphs.

It was first suggested by Stokes that during sound transmission through tubes there arises a frictional force which causes damping to the sound waves. This frictional force is considered to be due to a layer of fluid on the surface of the tube which is in laminar motion ; the thickness of this layer is very small and is given by Δ, which from theoretical considerations is found to be

$$\Delta = 2\pi\sqrt{\frac{2\nu}{\omega}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

where ν represents the kinematic viscosity and $\frac{\omega}{2\pi}$ the frequency of vibration. This view has been supported by Lamb, Rayleigh and others. Thus we come to a startling conclusion that to account for the decrease of absorption coefficient for a tube of given radius the value of Δ must increase with intensity of sound waves, that is, the thickness Δ of the laminar layer must increase. From our experiments, however, it is not possible to calculate the value of Δ. It may be noted in this connection that formulas (4) and (5) are based on a theory which assumes that the porous substance at which reflection occurs is an ideal substance which is a regular assemblage of a large number of similar channels of circular cross-section and thin wall, uniformly distributed and bounded by surfaces everywhere perpendicular to the face. It is, therefore, evident that even our vaccine tube specimen does not come up to the mark, as there are in it two types of channels (§5, Fig. 10) of a widely different nature, (b-type channels are not circular) and, hence, the reflection at such a surface is a complicated affair.

According to the theory developed by Sexl (1928), the particle velocity u at any radial distance r, in the case of alternating flow through a tube of radius 'a', is given by

$$u = c_1\{(\text{ber}\ \alpha a - \text{ber}\ \alpha r)\sin\omega t + (\text{bei}\ \alpha a - \text{bei}\ \alpha r)\cos\omega t\} \quad \ldots \quad (7)$$

where

$$\alpha = \left(\frac{\omega}{\nu}\right)^{\frac{1}{2}} \quad \text{and} \quad \frac{\omega}{2\pi} = \text{frequency.}$$

It is found that for small values of $\omega_{\rightarrow 0}$ the velocity u follows Poissieulle's law, viz. :

$$u = (a^2 - r^2)\,\frac{P_1 - P_2}{4l\eta}.$$

While when αa is large corresponding to increasing frequency, it is found that the velocity is practically constant along the radius except near the surface of the tube where the velocity vanishes. Thus we find that near the surface of the tube there exists a layer where the motion is laminar.

Experiments on alternating flow through tubes have been performed by Richardson and Tyler (1930) who have measured the velocity gradient in a transverse direction near the mouth of pipes ; their result confirms the above theory in a most remarkable manner. The thickness of the laminar layer Δ has been found to vary with frequency in the manner predicted by the theory, viz.

$$\Delta \propto \omega^{-\frac{1}{2}}.$$

The phenomenon near the open end of the pipe (at the other end a vibratory piston worked) is found to be very complicated, the peaks become very prominent and sharp and the velocity gradient along the radius does not follow Sexl law. As we recede from the open end, the peaks become less prominent and shift their position with respect to the wall of the tube (Fig. 13). The shift is towards the wall indicating a decrease in the value of Δ. With an increase of frequency, the same phenomenon is found to repeat itself with greater prominence and sharpness (Δ is measured from the peak to the surface of the pipe).

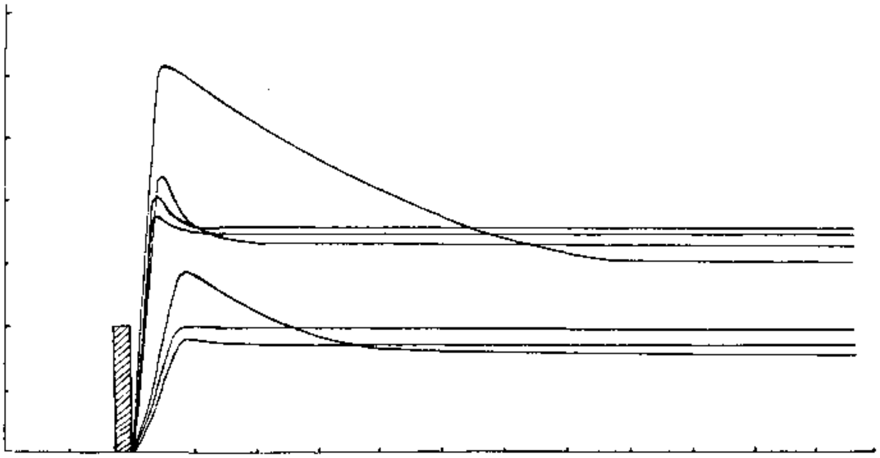

FIG. 13.

Curves showing velocity of air particles measured along the radius of the pipe at varying distances from the mouth of the pipe.

These results are of great consequence in the calculation of acoustic impedance at the open end of a tube. In calculating the impedance we generally assume that the type of motion at the open end is exactly the same as in the interior. According to experiment, however, we find that this is not the case. Hence, the impedance as calculated on the above basis will not represent the true value indicated by eqn. (5). We have already observed that the value of Δ near the open end is entirely different from that which exists in the interior of the tube. There is a decided increase in the value of Δ at the open end. Thus, the calculated value of the reflection coefficient will be larger and hence the absorption coefficient α for a porous material will be smaller than that calculated on the basis of formula (4).

But we have so far no direct experimental evidence to support the view that Δ near the open end undergoes a further change in the value with the increase of the intensity of sound waves. It has been found during the course of the determination of the nodal point that the latter shifts its position with the intensity.* Since the wave-form is not sinusoidal but shows the presence of

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* The shift of the nodal point observed in the case of cotton-waste and hair-felt are set down in tabular form below:—

A. COTTON-WASTE.

	INTENSITY.		Total shift centimetres.	Relative shift of nodal point cms.	Percent. of total shift	α Approx.
	I_m	I_R				
1	75	30	4·84	0·00	0·0	0·77
2	75	60	4·79	0·05	1·0	0·76
3	75	90	4·69	0·15	3·1	0·75
4	75	120	4·65	0·19	4·0	0·74

B. HAIR-FELT.

	INTENSITY.		Total shift cms.	Relative shift of nodal point cms.	Percent. of total shift.	α Approx.
	I_m	I_R				
1	75	30	1·73	0·00	0·0	0·24
2	75	50	1·70	0·03	1·7	0·23
3	75	70	1·65	0·08	4·6	0·22
4	75	90	1·60	0·13	7·5	0·21
5	75	120	1·62	0·11	6·4	0·22

Here the total shift is the difference between positions of the nodes with the perfect reflector and with the specimen, respectively.

other components (Fig. 12), the phenomena at the surface of the porous material must become more complicated and the interpretation of the results become difficult. But the hot-wire microphone, coupled with the resonator, being a selective instrument there is no doubt that the nodal point, for the particular frequency, shifts with the increase of intensity. On the basis of physical independence of motion of different frequencies, we might assume that the nodal point near the surface of porous material will also undergo a shift. In the case of a porous material, the nodal point is virtually inside the porous body. With the increase of intensity the nodal point shifts towards the open end, and if the experimental evidence of Richardson and Tyler be taken into consideration we find a ready explanation of the increase of Δ.

Richardson (1926) has also pointed out that Δ varies with the roughness and the elasticity of the material of the tube. A large number of experiments performed to determine the tube-correction (1933) to account for the diminution in the velocity of sound in tubes also seem to indicate the dependence of Δ on the two factors mentioned above.

The phenomena, however, requires further investigation with pure sinusoidal notes before any definite conclusion can be drawn regarding (1) the shift of the nodal point, and (2) the changes in the value of Δ near the open end at high frequencies. The theory so far known relates, it must be observed, to the phenomena inside the tube.

In conclusion I should like to offer my thanks to Professor M. N. Saha, F.R.S., for his kindly interest and to Dr. R. N. Ghosh, D.Sc., for his critical suggestions and help throughout the work. I also wish to express my thanks to the authorities of the Osmania University of Hyderabad, particularly Pro-Vice-Chancellor Qazi Mohammad Husain, for granting a scholarship which enabled me to stay at Allahabad and carry out this work.

ABSTRACT.

An experimental study of the variation of sound-absorption cœfficient α with intensity of sound was made by means of the stationary-wave-method. The materials employed in the investigation were (1) cotton-waste, (2) treetex, (3) hair-felt, (4) tool (a kind of thin cloth) and (5) an artificial specimen, which was an assemblage of a large number of capillary glass-tubes. It is observed

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The virtual node in the case of a specimen is situated somewhere inside the body of the specimen and so, in other words, the total shift is the distance of the virtual node from the surface of the specimen. It may be noted (Tables A and B) that as α decreases the virtual node shifts towards the surface of the specimen, and in the limit, that is when $\alpha_{\rightarrow 0}$ (Perfect Reflector) the virtual nodal point is at the surface of the substance and hence there is no shift of the nodal point with variations of the intensity of sound.

During the shift-measurement experiment, the room temperature was almost constant and the effect of change in frequency of the note (7 parts in 10,000) on the quarter-wave length, and hence on the shift, is negligible.

that an increase in the intensity of sound causes an appreciable decrease in the absorption coefficient of these substances. For an increase in sound-intensity from 25 d.b. to about 55 d.b, the decrease in α, in the case of cotton-waste and tool, is found to be linear and about 5% and 6% (of itself), respectively. In the case of felted substances (2) and (3), α at first decreases with intensity and after reaching a minimum value begins to increase with further increment in sound-intensity. The maximum decrease in α for (2) and (3) is as much as 15% and 25% (of itself), respectively. In the case of glass-tube specimen the decrease in α is about 7% for a change of intensity from 25 d.b. to about 60 d.b.

In explaining the results, the idea is put forward that an increase in the intensity of sound-waves increases the thickness of the layer of laminar flow or the 'skin' of gas which exists at the surface of the tube when the gas oscillates.

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