THE VELOCITY OF SOUND WAVES IN TUBES.

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In 1862–63 Regnault, in Paris, made an elaborate series of experiments on the velocity of sound in newly laid water pipes. As sources of sound he used a pistol, explosions, and musical instruments. Both ends of the pipe were closed and the sound was produced at one end. Thus the wave passed back and forth through the pipe many times, its time of arrival at the ends being recorded on a chronograph drum by a stylus operated electrically when the sound wave impinged on a thin membrane and closed an electric circuit. Figure 1 shows graphically the results of Regnault's experiments.

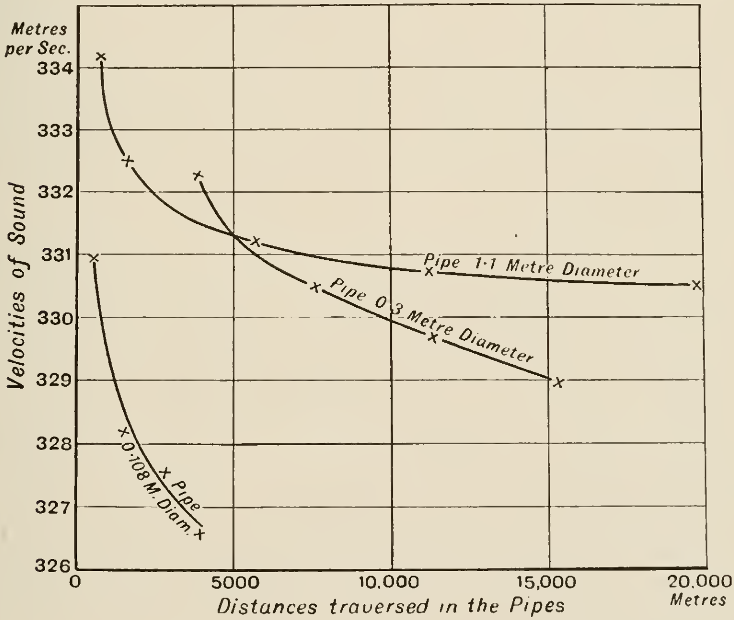

Fig. 1.

It will be noted that Regnault obtains a velocity of 334.2 m./sec. near the source in a pipe 110 cm. in diameter, and that the velocity at 2,000 m. from the source has decreased to 330.5 m./sec. A pipe 10.8 cm. in diameter gave a smaller initial velocity and a much more rapid variation of that velocity with distance from the source. (The curve indicates, too, a much greater total variation in the case of a small pipe.) Regnault concluded that: (1) The velocity of sound in pipes varies inversely with the diameter; (2) the velocity decreases as the distance from the source increases; (3) the limiting velocity is the same for all sources.

Rink objected to Regnault's deductions and explained the greater initial velocity as due to the fact that, during the first few coursings, the sound wave would be traveling in air moving bodily as the result of the explosion which produced the wave.

TABLE I.

Rink's Analysis of Regnault's Experiments.

No. of Experiment.	Charge of Gun Powder in Pistol in Gms.	Speed in cm. per Sec. of Each Passage of Sound Along Pipe 110 cm. Diameter.						Mean Speed for Given Charge of Powder
		3rd Passage	4th Passage	5th Passage	6th Passage	7th Passage	8th Passage	
1	0.5	330.02	330.29	330.15	330.21	330.11	330.13	330.152
2	1.0	330.36	330.59	330.57	330.61	330.44	330.42	330.498
3	1.5	330.29	330.57	330.54	330.47	330.47	330.53	330.433
4	2	330.60	330.51	330.84	330.44	330.44	330.30	330.513
5	1	330.04	330.26	330.26	330.23	330.15	230.22	330.193
6	1	330.36	330.37	330.50	330.67	330.55	330.50	330.492
Mean Speed for each Passage		330.278	330.428	330.477	330.452	330.360	330.350	

The above table gives the results of Rink's analysis of Regnault's experiments and appears to confirm Rink's contention that the true velocity of sound in a given pipe is constant, the result for a pipe 110 cm. in diameter being 330.5 m./sec. For a pipe 7 cm. in diameter LeRoux, using Regnault's methods, obtained a velocity of 330.66 m./sec.

Regnault, in 1865, by the reciprocal firing of guns, the explosion breaking an electrical circuit at the source, the wave—by moving a membrane—breaking another circuit at a distant point, both circuits making stylus records on the same chronograph, obtained velocities of 331.37 m./sec. and 330.7 m./sec. at distances respectively of 1,280 m. and 2,445 m. from the source. In all of Regnault's experiments efforts were made to determine and to correct for the time lag of the recording apparatus. The error due to this cause can not be entirely eliminated for two reasons. In the first place the lag depends on the intensity of the wave and is therefore a function of the distance from the source.

In the second place the sound produced by a pistol or cannon is, near the source, a pulse whose wave curve is short and steep. As the distance from the source increases the wave type changes. This change of wave form would of itself cause a variation in the time lag of the device. However, the unavoidable sources of error in Regnault's work are not sufficient to cast doubt on his conclusions that the velocity of sound decreases as the intensity decreases. Indeed, other experimenters using other methods have arrived at a similar conclusion, a conclusion in accord with theory.

Referring to Rink's table of Regnault's results from which Rink concludes that the velocity of sound in a pipe 110 cm. in diameter is practically constant, one may conclude that the apparent constancy is due to the fact that, in such a tube, the intensity of the sound wave varies very slowly with the distance from the source. In very small tubes and in tubes with rough walls or with walls of material capable of absorbing some of the energy of the waves, the intensity would vary more rapidly with increasing distance from the source, and one would expect a greater variation in the velocity. Experiments confirm this conclusion.

TABLE II.

Observer	Method	Frequency	Diameter and Material of Tube	Velocity m./sec.
Wertheim, 1844	Organ Pipe		1.0 cm. Brass 2.0 cm. Brass 2.0 cm. Glass 4.0 cm. Brass	329.12 330.11 330.23 332.10
Regnault. Mem. de l'Acad. Paris. 37. I. 3. 1868. C. R. B 66. s 209, 1868.	See Fig. 2 and explanation.			
Rink, Pogg. Ann. B 149 s 533. 1873.	See Fig. 2 and explanation.	Explosion	110 cm. Iron	330.5
Kundt. Pogg. Ann. B 135 s 333 u. 527. 1868.	Double Kundt's tube	?	3.5 cm. Glass 6.5 cm. Glass 13.0 cm. Glass	305.42 323.00 329.47
Seebeck. Pogg. Ann. B 139 s 104, 1870.	Kundt's tube	320 320 320 512 512 512	.34 cm. Glass .9 cm. Glass 1.75 cm. Glass .34 cm. Glass .9 cm. Glass 1.75 cm. Glass	317.26 328.02 329.24 322.98 328.44 330.92
Le Roux. Ann. Chem. Phys. (4) 12. 345, 1867	Similiar to Regnault's method	Explosion	7.0 cm.	330.66
Blaikley. Phil. Mag. V 16 p. 447, 1883.	Special form of organ pipe.	105	1.17 cm. Brass 1.95 cm. Brass 3.25 cm. Brass 5.41 cm. Brass 8.82 cm. Brass	324.56 326.90 328.78 329.72 330.13

TABLE II—Continued.

Observer	Method	Frequency	Diameter and Material of Tube	Velocity m./sec.
J. Muller. Ann. d. Phys......... B 11, s 331. 1903.	Kundt's tube..........	903	.372 cm. Glass....	317.2
		903	.678 cm. Glass....	322 9
		902	1.552 cm. Glass....	327.3
		2,482	.372 cm. Glass....	323.0
			.678 cm. Glass....	325.4
			1.552 cm. Glass....	330.2
Schulze. Ann. d. Phys.......... B 13, s 1060. 1904.	Quincke's double tube	384	.101 cm. Glass....	258
		384	.151 cm. Glass....	282
		512	.101 cm. Glass....	265
		512	.151 cm. Glass....	290
		384	.099 cm. Brass ...	189
		384	.148 cm. Brass....	230
		512	.099 cm. Brass....	208
		512	.148 cm. Brass....	253
		512	.150 cm. Rubber..	195

In Table II, I have tabulated some of the results obtained by a few of the many observers who have determined experimentally the velocity of sound in tubes. The results shown are not uniform, but in general they tend to show that—

(1) The velocity of sound in tubes is less than in free air.

(2) The smaller the tube the smaller the velocity.

(3) The higher the frequency the less the retardation.

(4) The velocity depends more or less upon the material of the walls of the tube.

(5) The greater the intensity of the sound the greater is its velocity.

The last-named conclusion is not drawn from Table II, but from the original papers there referred to. It must be said, however, that the observers referred to are not a unit in supporting the five conclusions above named. Other observers are equally at variance. For instance, Violle and Vautier[1] after a study of the velocity of sound in a masonry conduit 3 m. in diameter, the sounds being produced by various musical instruments and ranging in frequency from 32 to 640, arrived at the conclusion that in such a pipe the velocity is constant to within one part in a thousand. Rink's analysis of Regnault's results, given in Table I, would seem to show a velocity independent of sound intensity.

As a whole, however, the conclusions given are supported by experi-

[1] Violle and Vautier. Ann. Chem. Phys. (8) 5. 208, 1905.

ment, and are in accord with the theoretical conclusions of Helmholtz,[1] Kirchoff,[2] Rayleigh,[3] and others who have attacked the subject. The equations of both Helmholtz and Kirchoff may be reduced to the form

$$v^1 = v\left(1 - \frac{c}{2r\sqrt{\pi n}}\right)$$

where v^1 is the speed of sound of frequency n in a pipe of radius r, and v is the velocity in free air. According to Helmholtz c is the viscosity of the gas, according to Kirchoff it is a term depending on the heat conduction between gas and pipe walls, according to Müller[4] the equation has no general validity, according to Schulze[5] the "constant" c was found to range between 0.0075 and 0.025, depending on the diameter and nature of the tube.

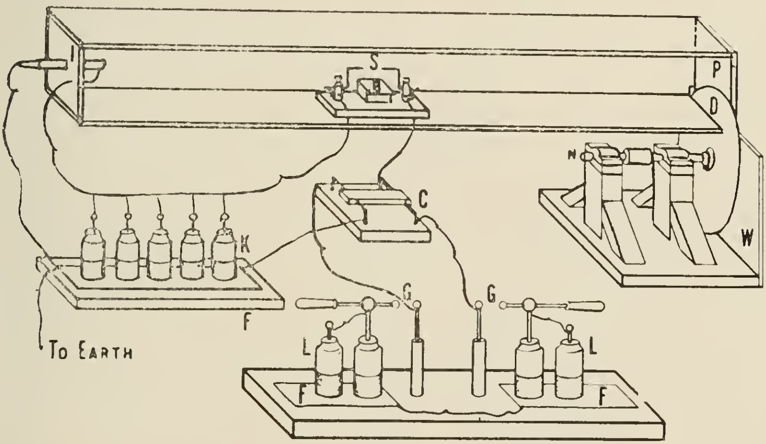

Fig. 2.

Sturm[6] found that Kirchoff's formula was not valid for different tubes and frequencies. On the other hand Wertheim's[7] results supported the equation, while Schneebele[8] and Seebeck[9] obtained results that sup-

[1] Helmholtz, Wessensch. Abhandl. B 1, s 383, 1882.

[2] Kirchoff, Pog. Ann. B 134, s 77, 1868.

[3] Rayleigh's Theory of Sound, Vol. —, p. —. Also Lamb's Dynamical Theory of Sound, p. 190.

[4] See Table II.

[5] See Table II.

[6] J. Sturm. Ann. d. Phys. B 14, s 822, 1904.

[7] Citation in Table II.

[8] Pogg. Ann. B 136, s 296, 1869.

[9] See Table II.

ported the equation only as far as concerns variation of speed with diameter of pipe, and were in disagreement as to the effect of pitch. There is therefore no consensus of opinion on any of the points concerning the velocity of sound waves in tubes. It will be noted, however, that in no case has an observer claimed a greater speed in pipes than in the open. The writer has obtained such results.

Figure 2 shows the general arrangement of the apparatus used in this experiment. The reader is referred to earlier papers[1] for a more detailed description and explanation. It will suffice here to say that two spark gaps S and I are in series and connected—through two variable gaps G, G—to the terminals of a powerful electrostatic machine. When the gaps G and G are shortened a discharge passes through the commutator C to the circuit including the sound gap S and the illuminating gap I, the latter spark being retarded slightly by a variable capacity K. By varying the capacity K and the length of the gap I, the light from the spark at I can be adjusted to cast a shadow on a photographic plate P of the sound wave produced by the spark at S.

Plate I shows such a wave. The sound spark was produced just behind the center of the circular screen (a hard rubber disk) D, the screen being used merely to prevent fogging the dry plate by the light of the sound spark. T is an end-on shadow of a portion of a piece of brass tubing 3 cm. in diameter and 5 cm. long. The projecting arms are four pieces of brass tubing, respectively 0.25 cm., 0.48 cm., 0.8 cm., and 1.15 cm. in internal diameter, each of them 2.4 cm. long. They were soldered radially in holes whose diameters corresponded respectively to the outside diameters of the tubes. Almost half of the side wall of the supporting tube was then cut away, to permit the sound wave to travel out on one side in free air, while on the other side the wave was arrested except for the portions passing through the four radial tubes. The sound gap was placed as accurately as possible at the center of the supporting tube and the point of intersection of the axes of the radial tubes.

In order to show at a glance just what has happened with the position of the sound gap as center I have drawn a broken line circle. To avoid confusion I have drawn the circle C just outside the main wave W. It will be noted that the waves through the tubes lie well without the circle, showing that the waves in the tube traveled more rapidly than the wave in free air, and that apparently the velocities in the several tubes were the same, although the tube diameters were in the approximate ratios of 1, 2, 3 and 5.

On the negative from which Plate I is a reduced print the waves

[1] Physical Review, Vol. 35, p. 373, 1912. Also Proceedings Indiana Academy of Science, p. 305, 1915.

through the tubes measured .48 cm. in advance of the free air wave and the tube length shadows were 4.56 cm. long. Assuming that the entire gain in space traversed occurred while the waves were inside the tubes (an assumption which I think is not entirely true) we would have a relative increase of velocity within the tubes of $.48 \div 4.56$, or 10.5 percent.

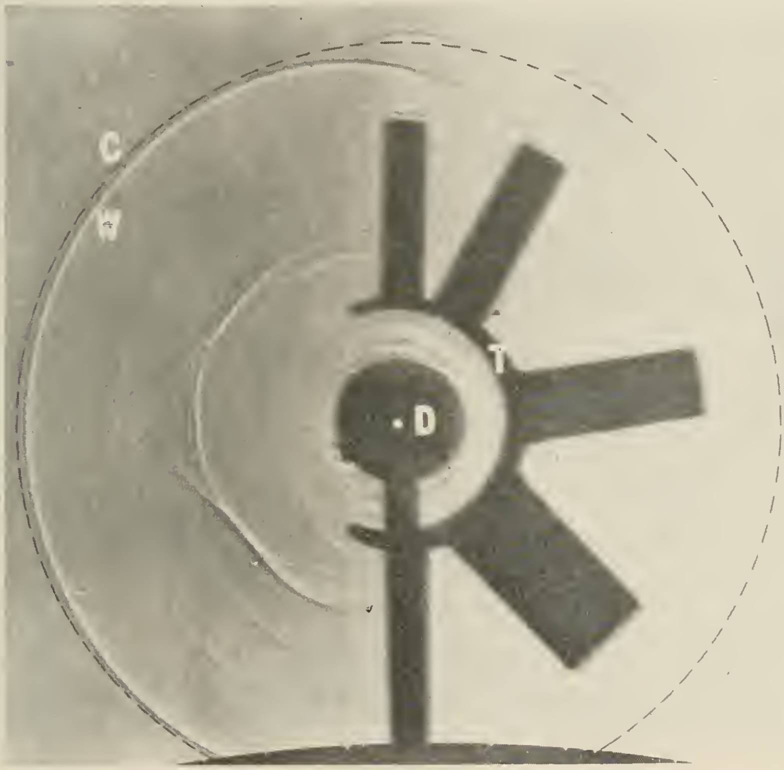

Plate I.

It happens that none of the observations of Table II was made with a tube of the same size as the smallest one used by the author. For a tube about 40 percent larger Seebeck and Müller obtained values approximately 5 percent less than the free air velocity—depending on the pitch of the sound. Thus it would appear that the total difference between their and the writer's results is in the neighborhood of 15 percent.

Plate II was obtained by replacing the four short tubes with two longer tubes, of internal diameter .25 cm. and 1.15 cm. respectively, each 10 cm. long, and adjusted radially as in Plate I. Note that in this case the wave through the small tube is actually slightly in advance of the wave through the large tube, the distances on the original plate

Plate II.

being .89 cm. and .84 cm. respectively. The wave near the gap is the reflected wave from the side of the box which enclosed the gaps and dry plate. The percent increase in velocity in this case is obtained as before by dividing .89 by 16.5, the length of the tube shadow on the negative. This gives 5.4 percent, about half the value obtained with the shorter tubes, which were about one-fourth as long as the two shown on Plate II. The gain in distance traversed was 0.48 cm. for the small tube when 2.4 cm. long, and 0.89 cm. when 10 cm. long. It would appear from this that more than half the gain was made in the first fourth of the tube's length, and that if the tube were long enough the velocity might drop to the values obtained by other experimenters, or even below —for their results are averages over considerable lengths of tubes.

The writer gives the calculations above—for Plates I and II—merely as an illustration of what occurred in these two cases, and not because he attaches any significance whatever to the numbers given. As a matter of fact, the numbers have no significance. In every case I have tried, the waves through the tubes have been in advance of those in free air, but the gain has been quite variable. I am now endeavoring to determine the cause of the increased velocity, and the reasons for its variation. I have secured a number of photographs of the waves through a 10 cm. and a 15 cm. tube placed side by side, with their ends at different distances from the sound spark. This investigation is not complete, but it has gone far enough for me to say that the velocity of a pulse through a tube is greatest when the end of the tube is nearest the sound spark, indicating that it is a question of sound intensity. The sound for a time travels faster in the tube than it does outside because the intensity of the wave in the tube decreases less rapidly than in free space.

This experiment appears to settle conclusively the question as to the dependence of sound velocity upon intensity independent of any variations caused by motion of air in a body, as contended by Rink in the case of Regnault's experiments. I shall discuss in a later paper the question of what happens to the air when a spark passes.

Physics Laboratory, Indiana University, January, 1919.