No. 1869

EFFECT OF PULSATIONS ON FLOW OF GASES

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The movement of gases and liquids when calculated by the existing hydraulic formulas presupposes a steady or continuous flow of the fluid. Anything which causes this flow to proceed in puffs, waves, or pulsations will result, by the action of metering devices, in errors often of great magnitude which generally do not admit of any adjustment, or of any definite knowledge of the amount of the error.

The present paper discusses work undertaken under the joint direction of the Engineering Experiment Station of the Ohio State University and the Research Sub-Committee on Fluid Meters of The American Society of Mechanical Engineers, which had for its object (a) *the study of the nature of the pulsation and* (b) *the discovery of some practical means of reducing or eliminating the pulsation or of compensating for its effects on the devices used for measuring fluid flow. The investigation was confined to the venturi meter, the orifice meter, the flange nozzle meter, and the pitot meter, using air flow from a small compressor discharging into a 3-in. line. It is believed, however, that the basic principles established by the experiments are fundamental for pulsating-flow conditions for gas, steam, and water as well as for air, and also for other sizes and kinds of installations.*

ONE of the most disturbing factors encountered in recent years in the metering of air, gas, steam, and water, especially in connection with all forms of power engineering, has been that due to turbulent or pulsating flow. This has not been confined to any one class or type of meter, but is present to a more or less degree with all forms of metering devices.

2 The measurement of gases and liquids when calculated by the existing hydraulic formulas presupposes a steady or continuous

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[1] Robinson Research Fellow, The Ohio State University.

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3 The work described in the present paper was undertaken under the joint direction of the Engineering Experiment Station of The Ohio State University, and the Research Sub-Committee on Fluid Meters of The American Society of Mechanical Engineers. A sub-committee of the Fluid Meters Committee consisting of A. R. Dodge, H. N. Packard, and H. Judd was selected to take direct charge of the research work.

PURPOSE OF THE INVESTIGATION

4 The object of the investigation as outlined by the sub-committee in direct charge was twofold:

a To study the nature of the pulsation

b To discover some practical means of reducing or eliminating the pulsation, or of compensating for its effects on the devices used for measuring fluid flow.

5 As the work has proceeded it has been necessary to use a specific installation involving the flow of air only, and also to limit somewhat the scope of the investigation. The work is by no means considered to be complete, and it is the intention in the future to continue with the research so as to shed more light on many doubtful points that have arisen, as well as to try out a number of new suggestions.

6 For convenience, flow meters have been classified in two main divisions which may be called (1) positive meters, and (2) inferential meters. The domestic gas, or water, meter is an example of the first class. It is a displacement meter in which an actual volume of gas is introduced into a container of known size, and the quantity thus measured is registered on the meter.

7 In commercial installations of even moderate size, inferential meters are used almost entirely. In meters of this class some function of the quantity of fluid passing a given cross-section of pipe is measured and from this observation the actual flow is deduced or " inferred." Perhaps the most common function observed

in such meters is a pressure difference which is a quadratic function of the velocity of flow. This method can be made to give accurate results under steady-flow conditions, but when the flow is pulsating the accuracy of the measurement is seriously affected, if, indeed, not entirely destroyed.

8 Three general cases may be mentioned where this problem is of great importance: (1) The measurement of natural gas, both entering and leaving a compressor station where reciprocating compressors are used; (2) the measurement of air both entering and leaving large reciprocating air compressors, or blowing engines; and (3) the measurement of steam supplied to reciprocating steam engines. The steam flow is pulsating in character because the engine cuts off the steam supply during a considerable part of each stroke. In each of these cases the flow of the fluid has a regular, comparatively rapid, rhythmical pulsation, which occasions serious errors in measurement, especially where the measuring element is of the inferential type.

9 Similar pulsating conditions are present in water flow where reciprocating pumps are used. The problem, however, is more easily solved by the proper use of air chambers and surge tanks. Water hammer in pipe lines from whatever cause bears a striking similarity to the pulsating effect produced by an air-compressor valve.

10 We have confined our investigations to inferential meters. These meter elements as selected are the venturi meter, the orifice meter, the flange nozzle meter, and the pitot meter. Furthermore, we have been limited to air flow from a small compressor discharging into a 3-in. line; and hence our findings, strictly speaking, would be applicable only to installations of similar character. However, it would seem highly probable that the basic principles established by these experiments would be fundamental for pulsating-flow conditions for gas, steam, and water as well as for air, and also for other sizes and kinds of installations.

EQUIPMENT EMPLOYED IN THE INVESTIGATION

11 The experimental work was carried on in the Mechanical Engineering Laboratories of the Ohio State University, and was begun in May, 1920. A large part of the work was done during the summer vacations of 1920–1921. During the remainder of the two years devoted to the work such time was put in as could be spared

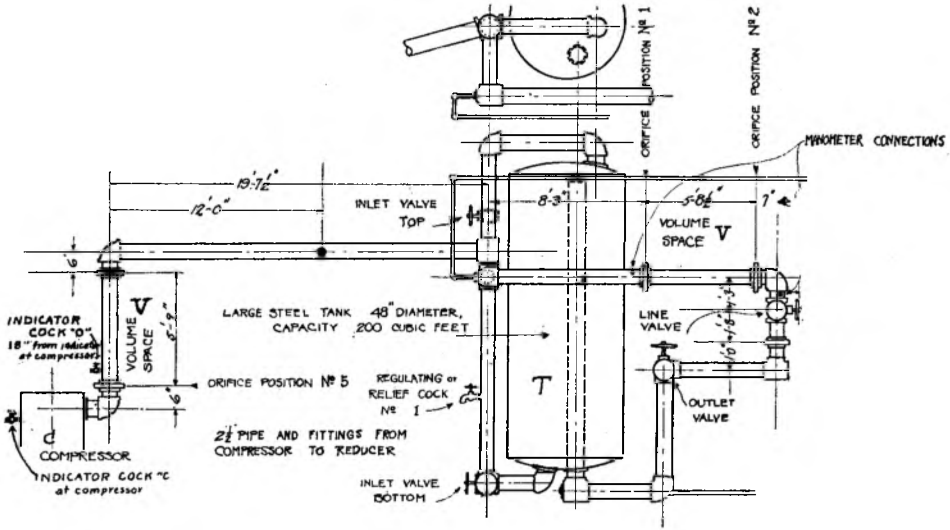

Fig. 1 General Layout of Apparatus — Left-Hand Portion

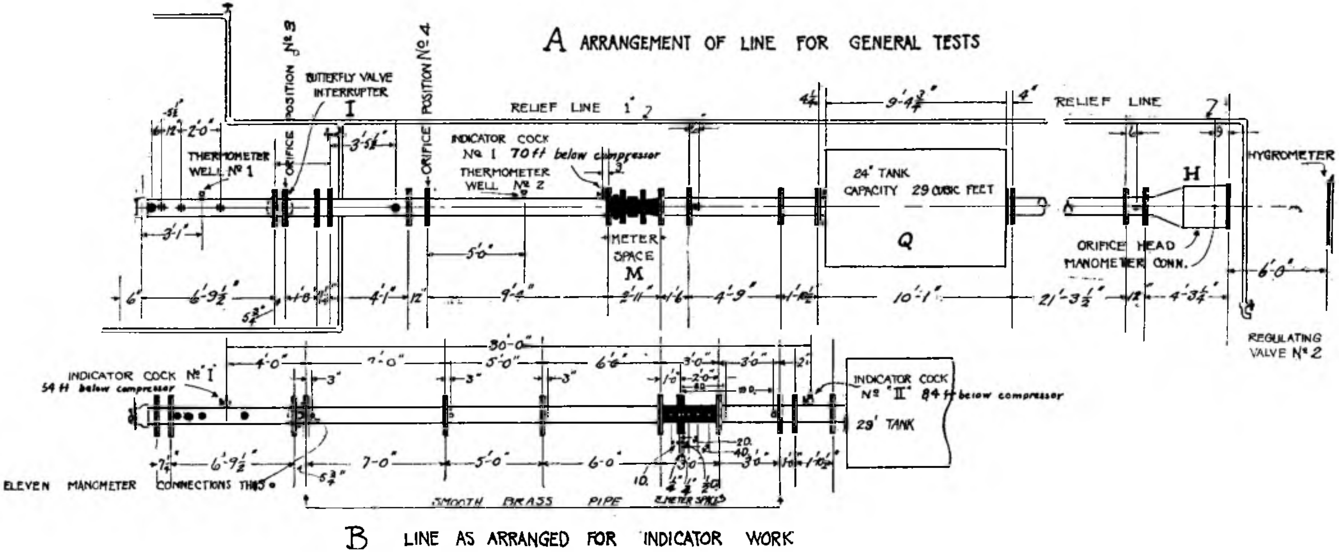

FIG. 1 GENERAL LAYOUT OF APPARATUS, RIGHT-HAND PORTION

from the university schedule. Acknowledgment should be made of the valuable service rendered by Mr. Paul Bucher,[1] especially during the vacation periods.

12 The essential elements for carrying on our project were: (1) a disturbing element to produce the pulsating flow; (2) a quieting element, or elements, to eliminate or modify the pulsations; and (3) a measuring element, to indicate constant flow conditions and also to indicate the effect of the pulsating flow.

13 *Disturbing Elements.* Fig. 1 shows the general layout of the apparatus, at the extreme left hand of which is located the air compressor *C*, a 9-in. by 9-in. single-stage, single-acting, gas engine-driven machine running at 293 r.p.m. This supplied air to a line about 120 ft. in total length of which 50 ft. was made up of 2½-in. pipe containing several short lengths and fittings. The remaining 70 ft. comprised the 3-in. test line of straight continuous length. This test line was at first made up of standard 3-in. black pipe of commercial quality; later 24 ft. of 3-in. brass pipe was substituted for that portion of the test line preceding the meter and extending 3 ft. below the meter section. (See Fig. 1, *B*.)

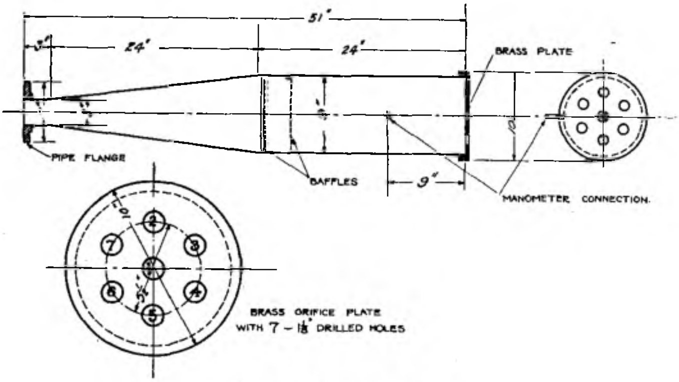

FIG. 2 ORIFICE HEAD

14 This air supply with its full pulsating effect could be admitted directly to the test line or could be first discharged through a large tank before entering the test line. A second disturbing element for producing pulsations artificially is shown at *I*, Fig. 1, the butterfly-valve interrupter. This butterfly valve could be

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[1] Assistant Professor of Steam Engineering, The Ohio State University.

driven at speeds ranging from 180 r.p.m. to 800 r.p.m., producing thereby a variation in the number of pulsations per second.

15 *Quieting Elements.* Considerable study was made of this essential feature and many trials were made to satisfy ourselves that we were securing pulsationless flow where and when needed. The tank *T*, Fig. 1, was used to quiet the pulsation before the meter station, *M*, was reached. This was a 48-in. vertical tank of 200 cu. ft. capacity. Air could be admitted either at the bottom or at the top and released from the tank through the internal pipe which reached nearly to the top. This tank when fitted with $1\frac{1}{4}$-in. orifices at top and bottom enabled us to get air flow free from pulsations before the test meters were reached.

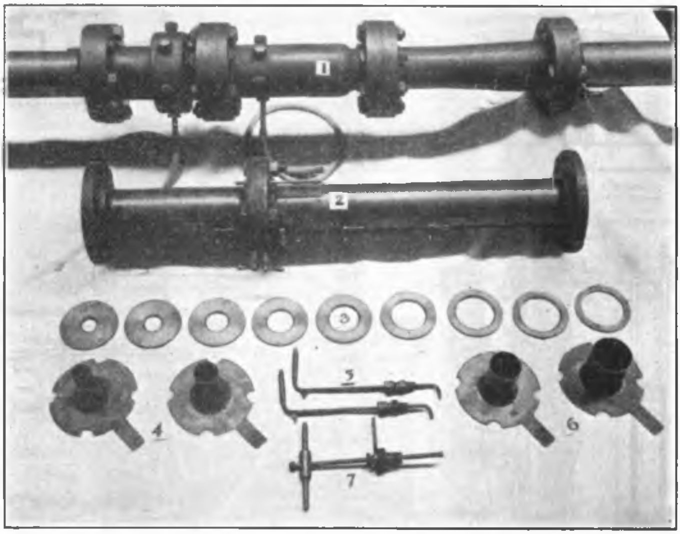

Fig. 3 Flow-Meter Units

16 A second quieting tank was inserted at *Q*, Fig. 1, at a point 8 ft. below the meter station. This was necessary in order to secure pulsationless flow at the orifice head for the purpose of establishing standard flow conditions. This tank was selected almost by chance and afterward was proved by test to be of sufficient capacity to eliminate practically all of the effect of the pulsating flow, and with the insertion of a $1\frac{1}{4}$ in. orifice at the exit from the tank we were entirely successful in securing pulsationless-flow conditions.

17 There are two positions marked, *V*, Fig. 1, one near the compressor and one just beyond the large quieting tank, where volumes of different sizes were inserted for the purpose of studying their quieting effect. Because the term volume seems to apply better we have perverted the word " volume " from a term meaning capacity to a special designation, and have used it altogether to denote the various tanks of different dimensions which have been used as quieting elements. Most of these volumes were used in the second volume space, *V*, beyond the large quieting tank.

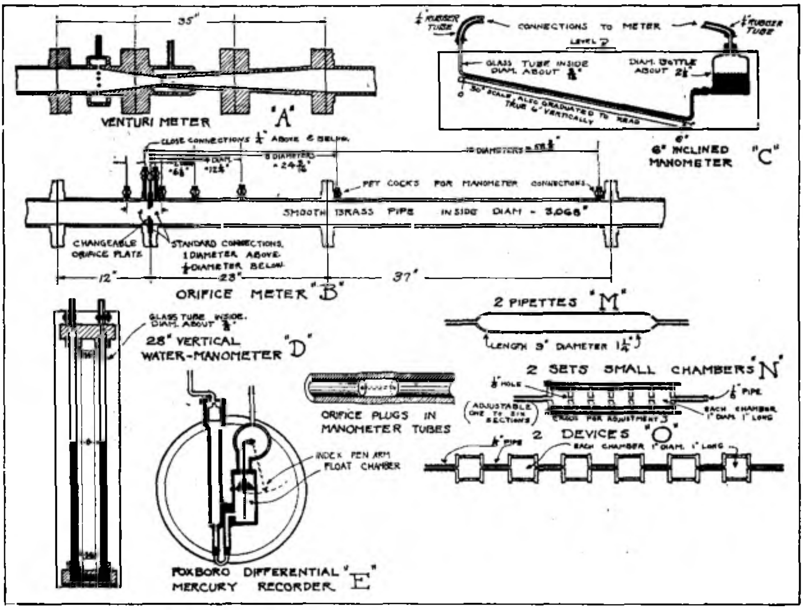

FIG. 4 SECTION SKETCHES OF METERS, MANOMETERS, AND CONNECTIONS

18 The line valve near the entrance to the 3-in. test line was used as a quieting element when employed as a throttling device. Both a gate valve and a globe valve and in some cases orifices were thus used as throttling devices.

19 The combination of throttling with volumes constitute the muffler type of quieting device. Fig. 7 shows an 8-section pipe-flange muffler which was also inserted in the line at the second volume station. This muffler is located in a by-pass in front of the line which runs directly from the compressor. All the volumes used

as quieting devices were placed in direct line, but later it was found that the by-pass position answered just as well for the muffler or the other quieting devices. Fig. 9, Nos. 1, 2, 3, 5, 6, shows some of the disks which were tried in the muffler. Fig. 8 shows sectional views of the pipe-flange muffler and also other forms of mufflers, including two funnel mufflers. A form of pulsating bag, Fig. 6, was used as a quieting volume and was connected to the compressor line in a way similar to an air chamber on a reciprocating pump. Another form of device used was a system of revolving fans or baffles. (See Fig. 9, No. 7.)

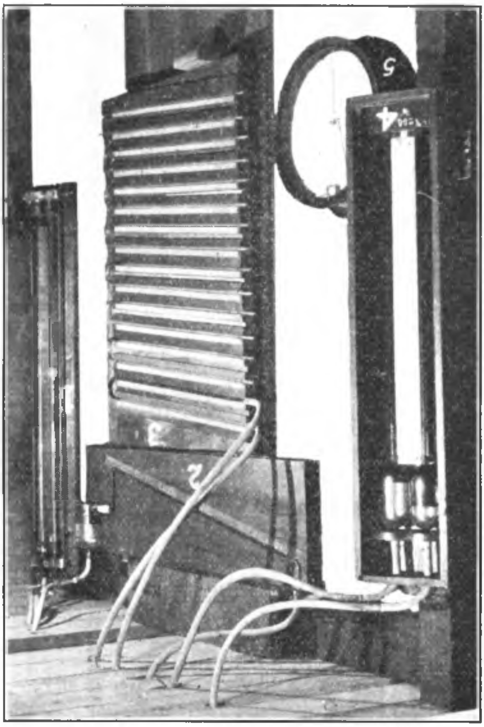

Fig. 5 Manometers Used with Flow-Meter Units

20 *Measuring Elements.* Under this heading will be taken up in order: (1) the orifice-head meter, (2) meter elements used, and (3) manometers used.

21 *Orifice-Head Meter.* It was recognized at the outset that one of the indispensable features was an accurate method of measur-

ing the discharge of the pipe, or (its equivalent) an accurate means of indicating the velocity of the air in the pipe. This was effected by means of an orifice head at the end of the pipe line, Fig. 1, *H*. Fig 2 is a detailed sketch of the orifice head. Its outer diameter is 9 in. for a distance of 2 ft., followed by a tapered section to meet the 3-in. line. This is given a taper of 7 deg., and was so chosen as being the limiting[1] angle for preventing as far as possible the swirling and eddying of the air as it passes into the orifice head from the line. Seven holes, reamed to 1⅛ in., were provided in the head plate ($\frac{3}{16}$ in. thick), although during the tests not more than

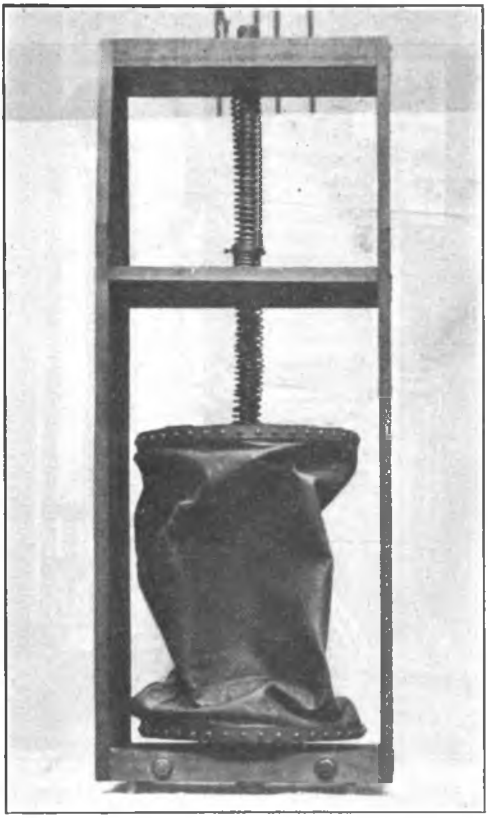

Fig. 6 Pulsating Bag

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[1] Trans. Am.Soc.M.E., vol. 42, 1920, p. 26: Physical Basis of Air Propeller Design, F. W. Caldwell and E. N. Fales.

five holes were used at one time. In general the capacity of the compressor was reached with four holes open with a standard static discharge head of 0.9 in. of water at the orifice head. The orifice head was calibrated by discharging air through it from the calibrated tank T under a constant static head at the orifice head. Readings every fifteen seconds were taken of this static head at the orifice head, giving 25 to 45 readings per run. The formula for a single orifice is:

$$q = KAV = 0.1261\,K\sqrt{h/W_a}$$

where q = air flowing cu. ft. per sec.
K = coefficient of discharge
h = static head at orifice head, inches of water
W_a = weight of 1 cu. ft. of air at temperature of flowing air at orifice plate.

For separate, single orifices the maximum value for $K = 0.6269$, the minimum, $K = 0.6037$; average for 13 runs, $K_m = 0.6086$. For orifices in combinations of twos, threes, fours, and fives, average of K for 22 runs including the single orifices $= 0.6115$.

22 The orifice head was also checked against a second orifice to show how uniformly the air was distributed in its cross-section. A variation was found between the center orifice and the surrounding single orifices ranging from 0.1 per cent below to 0.2 per cent above the ratio for the center orifice. The perforated baffles were then put in. These were two in number, the first being made up of a ¼-in. wooden strip screen with ¼-in. openings. Two inches in front of this wooden screen was placed a second perforated iron plate with 600 ¼-in. holes (see Fig. 2). All possible combinations of the orifices including single orifices and 5-hole orifices with and without the center orifice gave a variation not exceeding 0.1 per cent. This established uniform flow conditions in the orifice head regardless of the number of orifices open in the head plate.

23 For the standard 3-in. pipe (inside diameter, 3.068 in.) with a manometer head at the orifice head of 1 in. of water, barometer 29.50 in., humidity at 75 per cent, the velocity of air in the pipe for each orifice has been calculated as follows:

Temperature of air, deg. fahr.	Velocity of air in pipe, ft. per sec.
50	5.49
60	5.55
70	5.61
80	5.67
90	5.73

Wherever mention is made of the velocity of air in the pipe we have assumed 5.35 ft. per sec. for each orifice for a standard orifice head of 0.9 in. of water at 75 deg. fahr.

24 *Meter Elements Used.* The point of insertion of the meter elements in the line, Fig. 1, *M*, was about 70 ft. from the compressor, 50 ft. above the orifice head, and 25 ft. from the entrance to the 3-in. test line.

25 The venturi meter was a standard unit with 3-in. entry and 1-in. throat. It is shown attached to the pipe line in Fig. 3, No. 1, and in sectional view in Fig. 4, *A*.

26 The orifice meter, Fig. 3, No. 2, was made up of a flanged section of 3-in. brass pipe of the same length, 35 in., as the venturi section. The orifice flange, Fig. 4, *B*, was placed 12 in. from the upstream end and was counterbored to receive the set of orifice plates and to center them accurately. The downstream side of the hole in each plate was chamfered to $\frac{1}{32}$ in. in thickness, Fig. 3, No. 3.

Ratio of orifice and pipe diameters, per cent	Size of orifice plates: Diameter of orifice, in.
33	1.098
40	1.224
50	1.530
60	1.836
70	2.142
80	2.448
90	2.754
100	3.060

The manometer connections were made at one diameter above and one-half diameter below the orifice plate as the standard points of connection.

27 The flange nozzle meter was made by inserting in the orifice-meter section a special-shaped rounded-edge orifice with projecting cylindrical end, as in Fig. 3, Nos. 4 and 6. This nozzle

approximates the converging part of the venturi tube in shape. The manometer connections were made at one diameter above and one-half diameter below the flange, corresponding to the standard points of connection of the orifice meter.

28 Two forms of pitot tips were used. Fig. 3, No. 5, shows the hatchet-edge static tip (pitot No. 1) with ⅛-in. side openings. This is used with the accompanying open-ended impact tip with $\frac{3}{16}$-in. opening. Both tubes are made of ¼-in. seamless brass tubing. Fig. 3, No. 7, shows a modified form of pitot tip (pitot No. 2) having $\frac{5}{16}$-in. brass tubing and an impact or leading opening facing the direction of flow and a static or trailing opening directly opposite. The diameter of each opening is ⅛ in.

TABLE 1 SIZE OF FLANGE NOZZLES

Diam. of nozzle, in.	Inlet diameter at rounded edge, in.	Length, in.		
		Rounded edge	Cylindrical end	Total
1¼	3	1	2.375	3.375
1½	3	1	2.375	3.375
2	3	1	2.375	3.375
2½	3	⅝	2.750	3.375

29 *Manometers Used.* As far as possible the simpler forms of manometers were used. The vertical U-tube water manometer, as in Fig. 5, No. 1; Fig. 4, *D;* Fig. 10, *S,* was used with the venturi meter, and part of the time with the orifice meter and flange nozzle meter, and also for the static line pressure. Where the readings had to be magnified, use was made of a 6-in. inclined one-leg reservoir oil manometer, 5 to 1 magnification (Fig. 5, No. 2; Fig. 4, *C*). For certain other readings an inclined U-tube oil manometer and a vertical U-tube two-liquid manometer were used (Fig. 5, Nos. 3 and 4).

30 A Foxboro differential mercury recording gage, Fig. 5, No. 5 and Fig. 4, *E,* was used to make comparisons with the water manometer used with the venturi meter. The flow conditions were maintained and checked at the orifice head by means of an Ellison inclined gage of 1 in. range and 10 to 1 magnification.

NATURE OF THE PULSATION

31 The first knowledge of the nature of the pulsation was gained through the use of an instrument which we have called the "photopulsometer." This instrument was made and loaned to us by Mr. H. N. Packard of the Cutler-Hammer Co., Milwaukee, Wis. Its principle is similar to that of the "phonedeik" designed by Prof. D. C. Miller[1] of Case School of Applied Science and used by him in photographic studies of musical sounds.

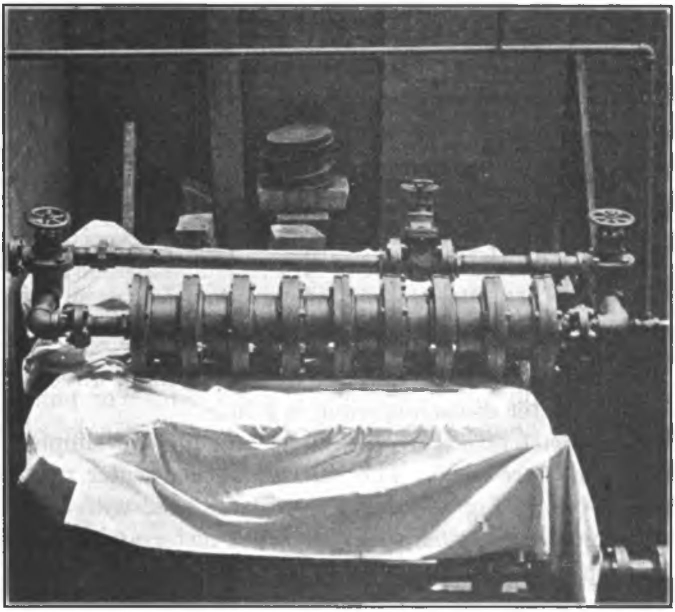

Fig. 7 Eight-Section Pipe-Flange Muffler

32 The photopulsometer is shown in the diagrammatic sketch of Fig. 11. A pitot tube with one leading and one trailing tip set with the opening in line on a vertical diameter was inserted in the center of the pipe. The leading or impact tip communicated with the under side of a diaphragm chamber. The trailing or static tip led to the upper side of the diaphragm chamber. The mica diaphragm, 0.011 in. thick, would therefore respond to changes in velocity of the air in the line as they occurred. These vibrations

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[1] The Science of Musical Sounds, p. 78, D. C. Miller.

were directly transmitted to a mirror hung in jeweled bearings and by means of a beam of light could be thrown on a photographic film giving a diagram proportional to the velocity. By means of a pendulum beating quarter- and half-seconds a chronographic record could also be made as shown on most of the films, for example in Fig. 14, by the breaks in the diagrams. A great many films were taken in this manner under a number of different running conditions and it proved to be a valuable method for providing a permanent record of the state of the flowing air in the line, either under violent pulsations due to various disturbing factors or for more steady flow due to the effect of certain quieting factors, as well as a record of the state of flow when under steady or pulsationless-flow conditions.

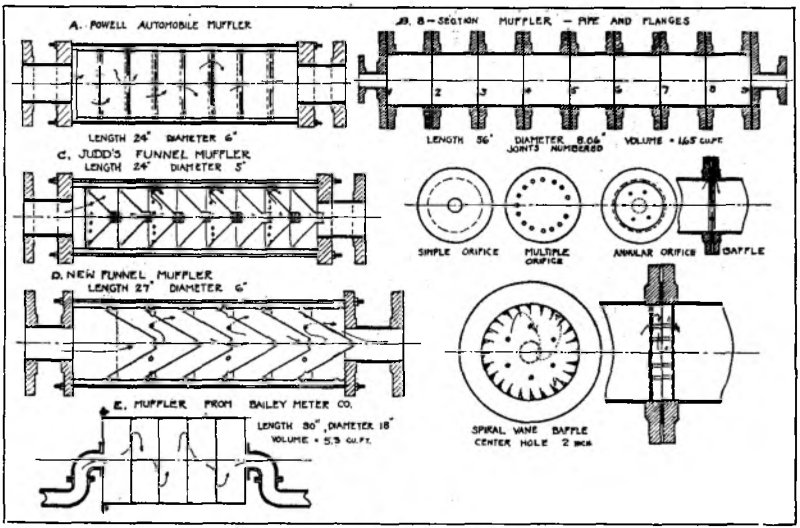

Fig. 8 Muffler Devices

33 *Velocity Diagrams.* Figs. 12 to 19, inclusive, give records of the velocity changes at the center of the pipe line at various points and under various flow conditions. The maximum effect of the pulsation in the open line direct from the compressor is shown in Fig. 12. There is little or no quieting effect due to a length of pipe equal to 183 diameters. As measured from the diagrams:

Average of maximum pulsation at 50 ft. from compressor = 1.05
Average of maximum pulsation at 111 ft. from compressor = 0.80
Square root of ratio of 80 to 105 = 0.875.

This equals 12.5 per cent quieting effect due to length of pipe for a maximum error of 82 per cent due to pulsating flow.

34 Fig. 13 shows artificial pulsations as produced by the butterfly-valve interrupter and that they are much less violent than those shown in the previous figure where the valve to the compressor is an automatic valve with a light spring. Diagrams (*a*) and (*b*) approach more nearly the shape of a sine curve. It should be noted that whenever the interrupter was used the air supplied came from the tank *T*, Fig. 1, used as a storage tank. The air was therefore free from pulsations except those that were imparted by the interrupter itself.

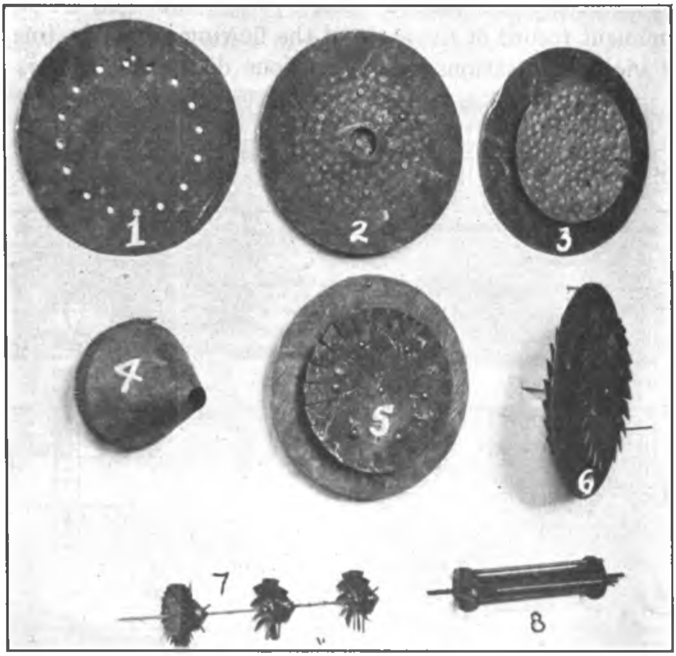

Fig. 9 Muffler Disks, Fan Units, and Small Quieting Devices

35 In Fig. 14 are shown artificial pulsations which are most violent near the interrupter. Those from a point 4 ft. [Diagram (*a*)] above the interrupter show only a slight disturbance indicating that the pulsation is retarded somewhat by the flowing current of air. Diagram (*d*), taken beyond the 24-in. volume,

shows its quieting effect and also shows the kind of diagram to be expected for pulsationless-flow conditions.

36 Diagram (*a*), Fig. 15, also shows pulsationless-flow conditions when the violent pulsations direct from the compressor have been eliminated by the use of the big tank *T* as a quieting device.

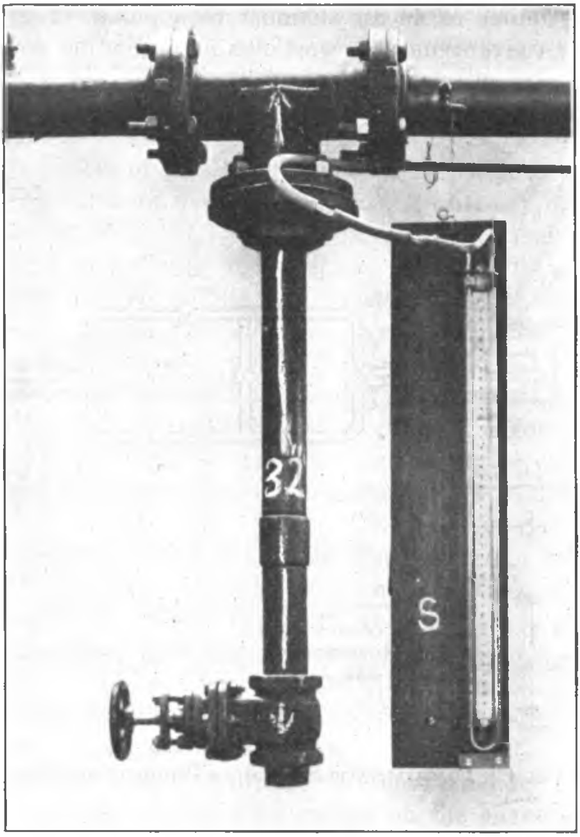

Fig. 10 Manometer for Pressure in Line

Diagram (*b*) shows that the diaphragm of the photopulsometer is not affected by the sound waves from a phonograph. Diagram (*c*) was taken to determine the natural period of vibration of the photopulsometer. This shows 6 vibrations in 0.103 sec., or 58 vibrations per second. This will explain the minute secondary pulsations occurring in Diagram (*a*) and in others under pulsationless flow. Most of the secondary pulsations seen in the other diagrams are likewise due to the same cause. Due to this cause also, some of the diagrams appear to go below the zero line when in reality they do not. Some other cases arise, however, where the pulsation appears to be negative, for which no good reason could be assigned.

37 The large tank *T* was tried as a quieting chamber, when connected similar to an air chamber to a pump. Fig. 16 shows that such an arrangement is worthless as a quieting device. This substantiates our later experience that, to be effective, tanks, or volumes, should be inserted in the line so that the air may pass through them axially.

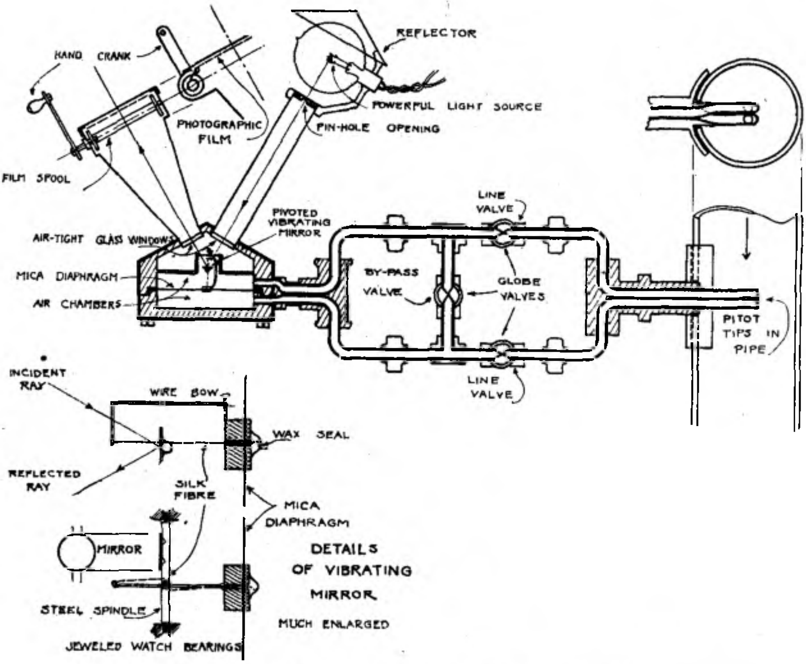

Fig. 11 Diagrammatic Sketch of Photopulsometer

38 One of the methods for eliminating pulsations is throttling by means of some kind of obstruction in the line such as a valve or an orifice. Diagram (*a*), Fig. 17, is taken for maximum pulsations direct from compressor. The diagrams appear to go below the zero pressure line, but when the secondary pulsations due to the natural period of vibration of the diaphragm are considered, it

will be seen that the true diagrams approach but do not go below the zero line. Diagram (*b*) shows the quieting effect of an orifice when the pulsation has been reduced to the condition of pulsationless flow.

39 *Effect of Pulsation of the Static Pressure in the Line.* For a compressor speed of 293 r.p.m., or nearly five revolutions per second, and for an air velocity in the pipe from 22 to 27 ft. per sec., the velocity wave length as shown by the diagrams would be from 4 to 6 ft. On starting the compressor it seemed frequently that the first impulse traveled much faster than the actual velocity of the air.

40 *Pipe-Line Pressure Diagrams.* To test this out and also to study the effect of pulsation on the static pressure in the line, two Crosby indicators were attached to the line, one on the compressor cylinder (Fig. 1, *C*), and the other 70 ft. distant (Fig. 1, *A*, No. 1 indicator) near the meter space. For details of arrangement of indicators for taking simultaneous pressure readings, see also Fig. 1, *B*. Diagrams from the compressor cylinder (Fig. 20, *A*, No. 1) had been taken several times before this as had also diagrams on indicator at point No. 1, Fig. 1, to show the rapid fluctuation in static pressure. When the indicator at point No. 1 was moved by hand a diagram was obtained closely resembling that shown on the films from the photopulsometer; but no diagrams had been taken simultaneously.

41 Since the sudden rise in the diagram taken by indicator No. 1 must mark the *beginning* of a pulsation, it was concluded that this initial point was the point at which the valve opened on the compressor, thus releasing a pulsation into the air line. This pulsation would continue with the upward stroke of the piston and at the instant that the valve on the compressor closed the pulsation on the record would cease.

42 The two indicator drums were connected by means of a light piano wire to the reducing motion on the engine. The two indicator pencil motions were connected by an electric circuit operating a detent motion. The pencil motion on the indicator at the compressor closed a switch and by means of a solenoid operated the pencil motion of the second indicator. Whenever simultaneous cards were taken, this method was used.

43 *Pressure Pulsation Greater Than Velocity Pulsation.* Three sets of such diagrams were taken and are shown at *A* and *B*, Fig. 20. Two important features were brought out: (1) The pulsa-

tion in the pipe produced a much greater pressure effect than that imparted to the velocity of flow. The diagram taken with the pitot tip (Fig. 20, *B*, No. 2) would be expected to give the combined effect due to pressure and velocity; and a larger and somewhat modified diagram might be looked for. On the contrary, the two diagrams taken with the static connection and with the pitot tip are strikingly similar in shape. (2) When simultaneous diagrams for a single stroke were recorded (Fig. 20, *A* and *B*, No. 3) it was found that the suction stroke of the compressor corresponded to the pressure stroke in the line. This seemed to indicate that the pulsation required about the time of a compressor revolution to travel a distance of 70 ft. in the pipe. For a speed of 291 r.p.m. this would mean about 0.1 sec. for ½ revolution, or a pulsation velocity of 700 ft. per sec.

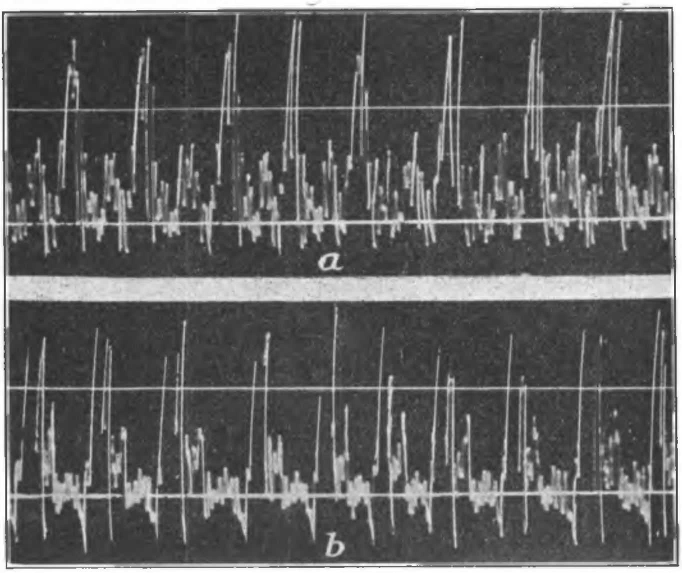

Fig. 12 Showing Maximum Effect of Pulsations at Different Points on the Line — No Quieting Effect Due to Increase in Length of Line

(*a*) Maximum pulsation in line 50 ft. below compressor. (*b*) Do., 111 ft. below compressor.

44 To verify this assumption, two more indicators were added and their location rearranged as shown in Fig. 1, *A* and *B*. The one at the compressor remained unchanged, a second (at *O*, Fig. 1, *A*) was placed 18 in. distant in the discharge line to establish the

beginning of pulsation (see Cards 14*c*, 14*o*, Fig. 21); indicators I and II (Fig. 1, *B*) were placed in the 3-in. line, 54 ft. and 84 ft., respectively, from the compressor. They were connected to the detent motion through the electric circuit and were arranged so as to be operated either by hand or by the reducing motion. In addition, sparking points were attached to indicators I and II and to the secondary coil, grounded through the pipe line, so that, by means of a commutator, the cards on Nos. I and II would be perforated simultaneously by twelve sparks for each revolution of the drum while operated by hand. (See Fig. 21, Cards 11_{I}, 11_{II}.)

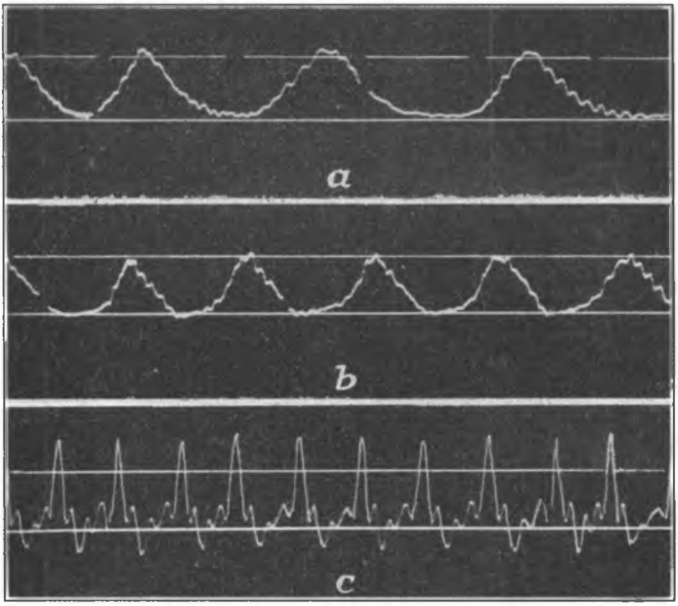

FIG. 13 PULSATIONS PRODUCED ARTIFICIALLY BY BUTTERFLY-VALVE INTERRUPTER. VELOCITY OF AIR IN LINE, 27 FT. PER SEC.

(*a*) 53 ft. below interrupter, 3 pulsations per sec. (*b*) 53 ft. below interrupter, 4 pulsations per sec. (*c*) 53 ft. below interrupter, 13.5 pulsations per sec.

45 *Analysis of Pressure Diagrams.* Fig. 21 comprises diagrams traced from cards taken on these indicators, including simultaneous cards at points *C* and *O*, *C* and *I*, *C* and II, *C*, I and II, and cards taken at I and II with coincident points shown by spark points. These diagrams include:

a Partial cards for establishing the fact that the initial point of pulsation is the initial point of pressure rise in the line which is seen to correspond to the point of valve opening in the compressor. (See diagrams to establish simultaneous pressure points, Cards 6*c*, 6*o*, 14*c*, 14*o*)

b Complete diagrams plotted in one direction, showing the use of the coincident lines. The drums were moved by hand and, at several points, simultaneous lines were drawn by means of the detent motion. This gives a method of accurate comparison of selected pulsations.

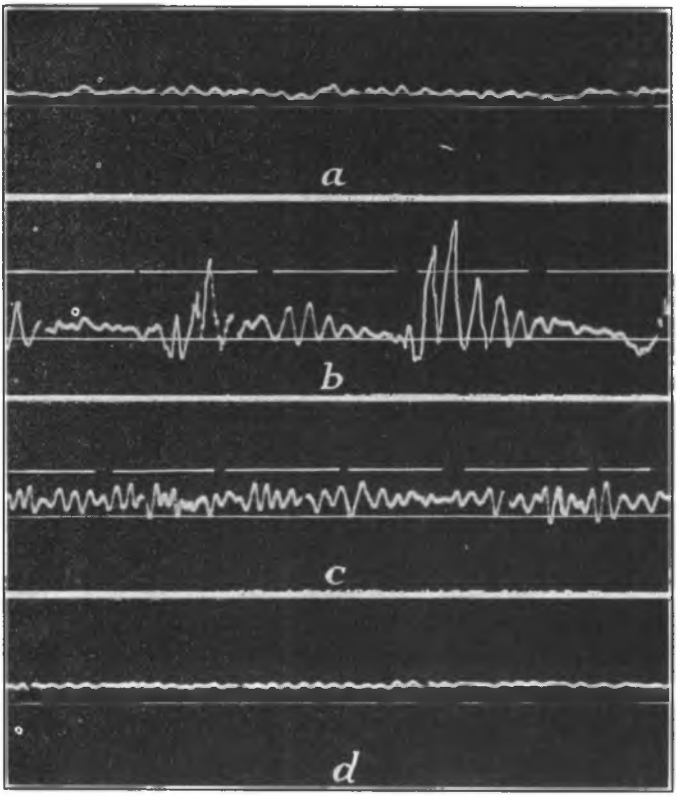

FIG. 14 SHOWING ARTIFICIAL PULSATIONS AT DIFFERENT POINTS IN THE LINE

Distances from butterfly-valve interrupter: (*a*) 4 ft. above; (*b*) 0.5 ft. above; (*c*) 2 ft. below (*d*) 60 ft. below, showing quieting effect of 24-in. volume.

c Also hand-operated diagrams to illustrate the initial pulsation points for repeated pulsations. The identity of the simultaneous strokes on the indicators is established and shown by means of the arrows of direction. (See Cards *3c*, *3o*.)

46 For the hand-operated cards the simultaneous lines are numbered alike and the initial points on the same pulsation at different points as it progresses are lettered *AAA*, *BBB*, *CCC*, etc. The progress of the pulsation down the pipe is shown clearly and the similarity of the shape as compared with the record from the photopulsometer is also apparent. (See Cards *3c*, 3_{I}, 3_{II}; 11_{I}, 11_{II}.)

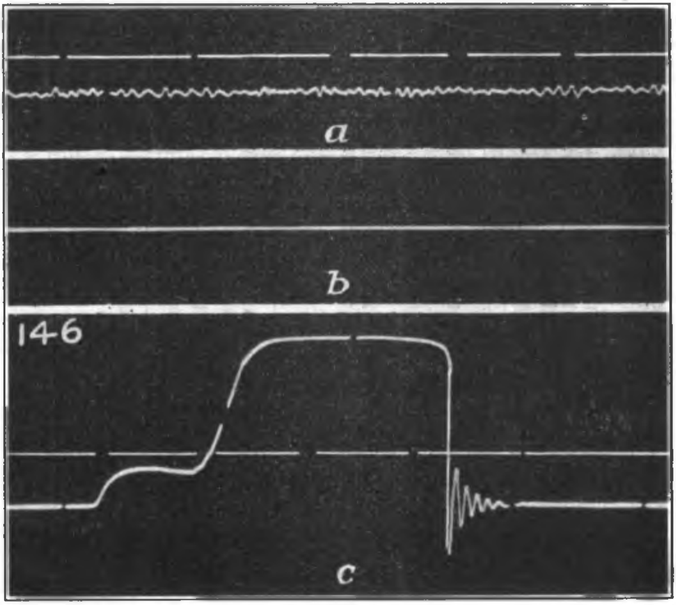

FIG. 15 SHOWING VELOCITY CONDITIONS FOR PULSATIONLESS FLOW, AND THE NATURAL PERIOD OF VIBRATION OF THE DIAPHRAGM

(*a*) Taken 111 ft. below compressor; air flowing from tank, no pulsations; velocity of air in line, 27 ft. per sec.

(*b*) Taken with tips placed in front of phonograph, sound concentrated in convergent nozzles.

(*c*) Showing the natural period of vibration of the photopulsometer.

47 *Rectification of Pressure Diagrams.* A few diagrams have been plotted to a uniform horizontal scale, or in other words, the diagrams have been converted into pressure-time diagrams. This method is clearly shown in Fig. 22. The motion of the piston has been considered as that of simple harmonic motion, which is not strictly true, owing to the finite length of the connecting rod. By plotting the complete pulsation as if the diagrams were taken in

TABLE 2 VELOCITY OF PULSATION IN PIPE

Computations of Velocity of Pulsation between Indicators I & II

Card No.	Coincident line	Pulsation measured	Length of pulsation in 100ths of an inch	Value of 0.01 in. in seconds of time	Distance from beginning of pulsation to reference line		Lead I-II 100ths of an inch	Time taken by pulsation to travel 30 ft.	Velocity of pulsation, ft. per sec.	Number of holes at orifice head	Remarks
					I	II					
10	4	C-D	72	0.00285	38	28	10	0.0285	1052	4—3.4.6.7.	
10	6	D-E	73	0.00281	43	34	9	0.0253	1185	4–	
10	8	E-F	62	0.00330	48	40	8	0.0264	1135	4–	R.p.m. = 293
10	9	F-G	63	0.00325	26	17	9	0.0292	1028	4–	
11	3	A-B	74	0.00277	24	13	11	0.0305	985	3–4.6.7.	
11	5	B-C	70	0.00293	28	17	11	0.0323	930	3	
11	7	C-D	55	0.00373	34	28	6	0.0224	928	3	
11	10	E-F	53	0.00387	45	38	7	0.0271	1106	3	

Computations of Velocity of Pulsation between Indicators C, I & II

Card No.	Coincident line	Pulsation measured	Length of pulsation in 100ths of an inch	Value of 0.01 in. in seconds of time	Distance from beginning puls. to line			Lead in 100ths of an inch			Time taken by pulsation to travel			Velocities, ft. per sec., based on distance		
					C	I	II	C-I	C-II	C-	54 ft.	84 ft.	30 ft.	54 ft.	84 ft.	30 ft.
5	2	A-B	145	0.00141	24	3	-10	21	34	13	0.0296	0.0480	0.0183	1830	1950	1640
5	6	B-C	122	0.00168	52	15	-4	37	56	19	0.0662	0.0941	0.0319	869	893	941
6	3	A-B	120	0.00171	42	21	5	21	37	16	0.0359	0.0632	0.0274	1510	1330	1095
6	6	B-C	110	0.00186	42	18	4	24	38	14	0.0446	0.0706	0.0261	1210	1190	1148
7	3	A-B	150	0.00136	32	-3	-18	35	50	15	0.0478	0.0683	0.0205	1130	1230	1465
7	7	B-C	105	0.00195	42	7	-12	35	54	19	0.0683	0.1052	0.0371	791	797	809

one direction only, the true characteristic shape of the pressure diagram is obtained. When the pulsation is foreshortened and repeated it bears a striking resemblance to those shown on the hand-operated diagrams in Fig. 22 and shown also on the film of the photopulsometer.

48 *The Velocity of the Pulsation.* The determination of the velocity of pulsation from the simultaneous sets of indicator diagrams for points I and II located 30 ft. apart was made as follows:

a Hand-operated diagrams were taken as previously explained.

b The diagrams were carefully compared, points of spark puncture located, coincident lines drawn thereform and numbered, and the initial points of the pulsations were identified and marked *AAA, BBB, CCC,* etc. The unavoidable irregularity of hand operation rendered the identical pulsations easily recognizable by means of their relative lengths.

c Measurements of the sets of diagrams were carried out, as shown in Table 2. It will be noticed that the computations shown include some of the diagrams illustrated in Fig. 21. All the diagrams shown are tracings of originals and are numbered and dated.

d Results were computed as shown on Table 2. Choosing Diagram 11 (see Fig. 21, Cards 11), coincident line No. 3, pulsation *A-B* is 0.74 in. long. For 293 r.p.m. one revolution = 0.205 sec. = time of one pulsation. If 0.74 in. or one pulsation = 0.205 sec., 0.01 in. = 0.00277 sec. Point *A* is 0.24 in. from line 3 for indicator I, and is 0.13 in. from line 3 for indicator II, a lead at point I over point II of 0.11 in., or the time taken to travel 30 ft. will be 0.00277 x 11 which is 0.0305 sec. Rate of travel per second = 30 ÷ 0.0305 = 985 ft., which is the velocity of pulsation. The velocity of sound in dry air at 0 deg. cent., 766 mm. pressure, is 1086 ft. per sec.

49 Table 3 gives the average results computed as in the example given and includes data taken for three points in the line, 30 ft., 54 ft. and 84 ft. from the compressor, and for six different velocities of air flow.

50 These results establish three significant facts:

a That, although our method shows results varying from the maximum to the minimum through a wide range, yet in no case does the velocity of pulsation so determined approach anywhere near the velocity of the flowing air.

b That, for a variation of velocity of flowing air ranging from zero to 27 ft. per sec., the velocity of pulsation was found to be independent of the velocity of the air.

c That the total average for 148 computations gave 1090 ft. per sec. as the velocity of pulsation. The velocity of sound in dry air at 32 deg. fahr. and 29.92 in. barometer is 1083 ft. per sec. The velocity of pulsation in all probability is equal to that of sound in air.

TABLE 3 AVERAGE RESULTS FOR VELOCITY OF PULSATION

Date	No.	Number of diagrams measured	Length of pipe used, ft.	Velocity of air per sec., ft.	Velocity of pulsation, ft. per sec.		
					Max.	Min.	Avg.
4-5-22	1	14	30	0	1462	640	1042
	2	16	30	5	1412	869	1088
	3	18	30	11	1440	805	1124
	4	20	30	16	1263	775	1019
	5	20	30	22	1290	815	1044
	6	13	30	27	1465	747	1100
	Total	101				Average...	1070
4-7-22	7	16	30	22	1640	809	1143
	8	15	54	22	1830	780	1107
	9	16	84	22	1750	797	1149
	Total	47				Average...	1133

51 For the average velocity of pulsation equal to 1090 ft. and for 4.88 pulsations per second, the pressure wave length as shown on the diagrams would be 223 ft.

52 Since the velocity of the pulsation is independent of the velocity of the flowing air and is evidently equal to the velocity of sound in air, it seems quite reasonable to conclude that the pulsation is a pressure change in the form of a wave front resembling a sound wave of low frequency. It seems also highly probable that these pulsations are similar in character to the pulsations set up by water hammer in a pipe line, since they also travel with the velocity of sound in water.

53 We gained some additional knowledge of the nature of the pulsation by noting its effect on manometers. Where a manometer was used to measure a differential head at a meter, the following effects were consistently present:

a For pulsationless flow the reading was very constant, the only variation being a slight long period surge due to appreciable variations in the compressor speed.

TABLE 4 OBSERVED DATA AT METER

No.	Setting of Line	Instrument Used	Readings on Manometer									Remarks
			1			2			3			
			Lt.	Rt.	Tot.	Lt.	Rt.	Tot.	Lt.	Rt.	Tot.	
1	9″×9″ vol. at compressor	Vent. 28″ Man.	12.9	13.2	26.1	12.8	13.3	26.1	12.7	13.3	26.0	Temp 2
2		" Foxboro	cha	rt	19.			19.			19.	= 86.5°
3		indicator card										R.p.m.
4		Film No. 255	at	Ia_2								=288
5	9″×9″ vol. at comp.	Vent. Foxboro			21.8			21.8			21.8	
7	9″×18″ vol. midway	" 28 M.	13.5	13.8	27.3	13.3	13.8	27.1	13.2	13.5	26.7	
10	9″×9″ vol. at comp.	" . "	11.7	12.1	23.8	11.7	12.2	23.9	11.7	12.2	23.9	
11	9″×27″ vol. midway	1 " Foxboro			20.6			20.6			20.6	Temp.
14	9″×9″ vol. at comp.	" "			20.0			20.0			20.0	= 99°
15	9″×36″ vol. midway	" 28″ M.	12.8	13.2	26.0	12.7	13.1	25.8	12.7	13.2	25.9	
18	9″×9″ vol. at comp.	" "	12.9	12.2	25.1	12.6	13.3	25.9	12.1	12.8	24.9	(Runs
19	9″×45″ vol. midway	" Foxboro			19.8			19.8			19.8	made
22	9″×9″ vol. at comp.	" 28″ M.	11.9	12.6	24.5	11.9	12.4	24.3	12.0	12.6	24.6	7–20–21)
23	9″×54″ vol. midway	" Foxboro			18.6			18.6			18.6	
26	9″×45″vol. at comp.	" Foxboro			21.0			21.0			21.0	
27	9″×54″ vol. midway	" 28″ Man.	12.0	12.6	24.6	12.0	12.7	24.7	12.0	12.7	24.7	
2	9″×45″ vol. at comp	Venturi meter with 28″ vertical water manometer	9.8	10.6	20.4	9.8	10.5	20.3	9.8	10.4	20.2	
5	9″×18″ vol. " "		14.1	14.4	28.5	14.1	14.3	28.4	14.2	14.3	28.5	R.p.m.
8	9″×27″ vol. " "		12.4	12.9	25.3	12.5	12.9	25.4	12.6	13.0	25.6	= 288
11	9″×36″ vol. " "		11.3	11.9	23.2	11.2	11.7	22.9	11.2	11.8	23.0	(Runs
14	9″×54″ vol. " "		8.8	9.7	18.5	9.1	9.6	18.7	9.0	9.7	18.7	made
17	Line Clear		15.8	17.0	32.8	15.9	17.0	32.9	15.7	17.0	32.7	7–21–21)
22	Pulsationless		4.1	5.1	9.2	4.1	5.1	9.2	4.1	5.1	9.2	
20	Pulsating — O.L.	1″ or 33% orifice meter with 28″ vertical water manometer	14.0	13.2	27.2	14.0	13.2	27.2	14.0	12.9	26.9	R.p.m.
22	Pulsationless		11.7	11.4	23.1	11.9	11.6	23.5	12.0	11.7	23.7	= 291
29	1–1″ Orifice		12.6	12.1	24.7	12.7	12.2	24.9	12.7	12.1	24.8	
30	2–1″ Orifices		11.8	11.4	23.2	12.5	11.7	24.2	11.5	12.5	24.0	T_2=95°
31	3–1″ "		12.2	11.5	23.7	12.2	11.5	23.7	12.2	11.7	23.9	(Runs
32	4–1″ "		12.3	11.6	23.9	12.1	11.5	23.6	11.6	11.6	23.2	made
33	5–1″ "		12.0	11.5	23.5	12.0	11.0	23.0	12.0	11.5	23.5	8–5–21)
2	1″ Orifice	33% orifice meter 28″ vertical manometer	13.9	13.3	27.2	14.0	13.4	27.4	13.8	13.3	27.1	R.p.m.
3	$\frac{28}{32}$″ "		12.3	12.0	24.3	12.5	12.2	24.7	12.4	12.1	24.5	= 291
4	$\frac{25}{32}$″ "		12.2	12.0	24.2	12.3	12.1	24.9	12.2	12.5	24.7	(Runs
5	$\frac{22}{32}$″ "		12.3	12.0	24.3	12.3	12.0	24.3	12.3	12.0	24.3	made
6	$\frac{19}{32}$″ "		12.4	12.1	25.5	12.7	12.3	25.0	12.7	12.3	25.0	8–6–22)

b For pulsating flow this surge was magnified greatly.

c For pulsating flow there is also a rapid vibration of the water column corresponding to the pulsations and depending in amplitude upon the local conditions at the manometer.

d The most significant characteristic of the readings for pulsating flow was the large increase over that for pulsationless flow. This increase was present for every type of manometer, meter and gage tried. It varied from a few per cent to several hundred per cent under extreme conditions.

THE ELIMINATION OF THE PULSATION

54 The problem of the elimination of the pulsation, or of the effects due to the pulsation, suggested two methods of attack: (1) modification of the existing metering devices so that the recorded flow would be unaffected whether the flow be steady or in pulsations; and (2) the use of devices which would correct or eliminate the pulsations before the flowing fluid reached the meter.

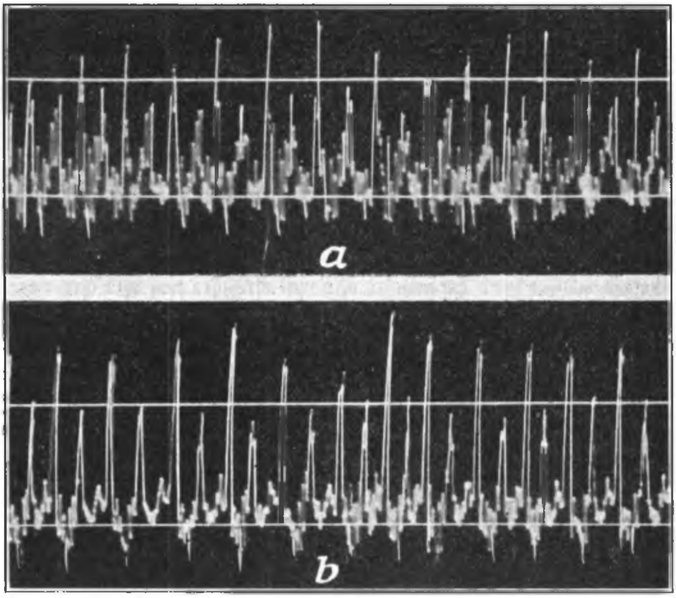

Fig. 16 Vertical Tank of 200 cu. ft. Capacity as Quieting Chamber—Similar to Air Chamber on Pump; 4.9 Pulsations per Sec.

Distances below compressor: (*a*) 50 ft.; (*b*) 117 ft.

55 The first of these suggested schemes was taken up to some extent in the study of the modification of manometer connection. The second suggestion, that of pulsation elimination, received the

major part of our attention. Of the five quieting devices used, the pulsating bag and the revolving fan operated by the air flow were studied by means of the photopulsometer. The use of throttling devices, the insertion of tanks, volumes or equalizing chambers in the line and a combination of the two devices, forming the so-called "muffler," comprise the remaining three quieting and eliminating devices. These five schemes, it is believed, cover nearly all, if not all, of the practical schemes which might be used for this purpose.

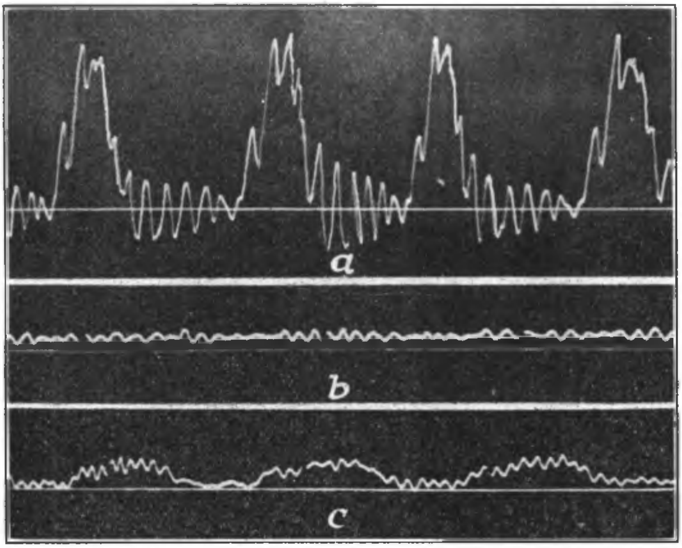

FIG. 17 SHOWING QUIETING EFFECT OF THROTTLING BY MEANS OF AN ORIFICE

(*a*) 80 ft. below compressor, maximum pulsation in line. (*b*) 10 ft. below throttling orifice, pulsation destroyed. (*c*) 4 ft. above interrupter, 3.5 pulsations per sec.

56 The tabulated results which follow include the average observed data and the percentage of error as figured from these average data. The average observed data are the averages of three simultaneous readings taken for all manometer readings. Tables 4 and 5 are observed-data sheets. In most instances where any change in line setting was made a pulsation-flow run was followed immediately by a pulsationless-flow run so as to eliminate the error due to possible change in temperature. In the few cases during the first of the experimentation where this was not done, proper corrections were made later for the temperature effect.

The term " percentage of error " for any meter means the percentage by which the indicated velocity of flow with pulsations differs from the velocity of flow for quiet or pulsationless flow, both readings taken on the same manometer, or indicating device and with a constant quantity of air flowing under the same conditions. The condition for constant flow was assured by maintaining at all times

TABLE 5 OBSERVED DATA AT ORIFICE HEAD

Run No.	Orifice-head reading			Hydrometer		Instrument or line setting	Remarks
	1	2	3	Dry temp.	Wet temp.		
1	0.911	0.914	0.911	79.0	70.0	Pulsating flow. No. 1. Vol. 9" × 9" next to compressor, others from No. 2 to No. 6 at mid point. Venturi meter — alternating Foxboro gage and water manometer.	Bar. = 29.047 Zero of orifice-head gage = 0.003 in. (Runs made 7-20-21)
2	0.929	0.913	0.916	78.6	69.8		
3	0.909	0.917	0.916	78.9	70.0		
4	0.915	0.909	0.900	79.3	70.1		
5	0.911	0.903	0.905	80.5	70.6		
7	0.917	0.890	0.877	80.4	70.6		
10	0.920	0.916	0.914	81.1	70.0		
11	0.897	0.892	0.890	81.1	70.1		
14	0.915	0.910	0.891	81.2	70.0		
15	0.878	0.875	0.881	81.0	69.8		
18	0.905	0.903	0.887	82.1	67.7		
19	0.902	0.898	0.901	82.6	67.8		
22	0.895	0.887	0.896	82.8	67.7		
23	0.900	0.895	0.884	83.5	68.0		
26	0.915	0.907	0.894	83.3	67.6		
27	0.905	0.913	0.910	84.0	67.9		
2	0.905	0.906	0.908	74.3	66.5	Open line pulsationless	Bar = 29.195 Zero = 0.004 in. (Runs made 7-21-21)
5	0.895	0.904	0.898	76.3	66.5		
8	0.900	0.893	0.890	77.0	66.6		
11	0.881	0.890	0.903	77.1	66.6		
14	0.880	0.882	0.896	77.9	66.8		
17	0.911	0.910	0.910	78.6	66.7		
22	0.894	0.906	0.911	79.3	68.1		
20	0.898	0.902	0.901	79.3	70.1	Open line pulsationless	Bar. = 29.051 Zero = 0.006 in. (Runs made 8-5-21)
22	0.910	0.906	0.913	79.6	71.2		
29	0.913	0.914	0.913	80.0	70.0		
30	0.895	0.920	0.911	80.8	70.5		
31	0.915	0.910	0.910	80.5	69.1		
32	0.913	0.917	0.906	80.9	69.8		
33	0.886	0.890	0.882	81.2	71.0		
2	0.910	0.902	0.908	72.5	63.5	1 in.	Bar. = 28.98 (Runs made 8-6-21)
3	0.916	0.920	0.919	73.5	69.5	$\frac{28}{32}$ in.	
4	0.915	0.920	0.930	74.0	70.0	$\frac{25}{32}$ in.	
5	0.925	0.928	0.930	—	—	$\frac{22}{32}$ in.	
6	0.930	0.945	0.940	75.0	70.5	$\frac{19}{32}$ in.	

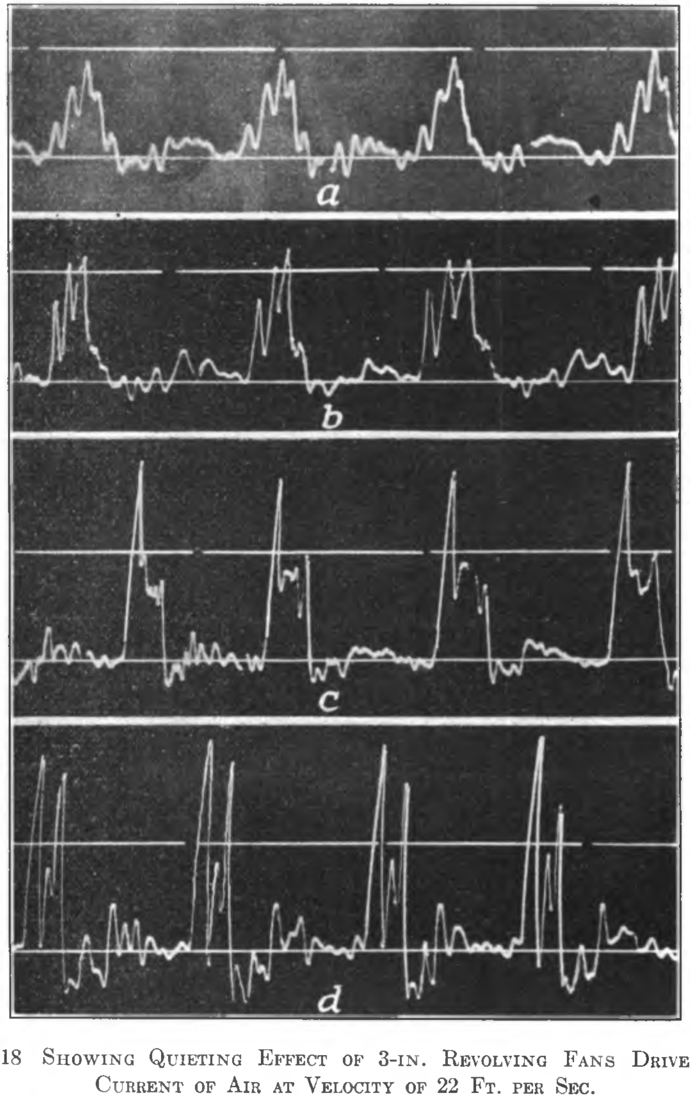

Fig. 18 Showing Quieting Effect of 3-in. Revolving Fans Driven by Current of Air at Velocity of 22 Ft. per Sec.

(*a*) 54 ft. below compressor, pulsation slightly throttled; maximum error due to pulsation, 68 per cent; 4.5 pulsations per sec.

(*b*) Same as (*a*) but at 80 ft. below compressor.

(*c*) 54 ft. below compressor, 6 ft. above fan section; maximum error due to pulsation, 68 per cent; 4.5 pulsations per sec.

(*d*) 20 ft. below fan section acting as quieting unit; error reduced from 68 per cent to 27 per cent; 4.5 pulsations per sec.

a static head of 0.9 in. of water at the orifice head, where special care was taken to secure pulsationless-flow conditions.

$$\text{Error in Per Cent} = (\sqrt{P_2/P_1} - 1)100$$

where P_2 = corrected manometer reading for pulsating flow
P_1 = corrected manometer reading for pulsationless flow.

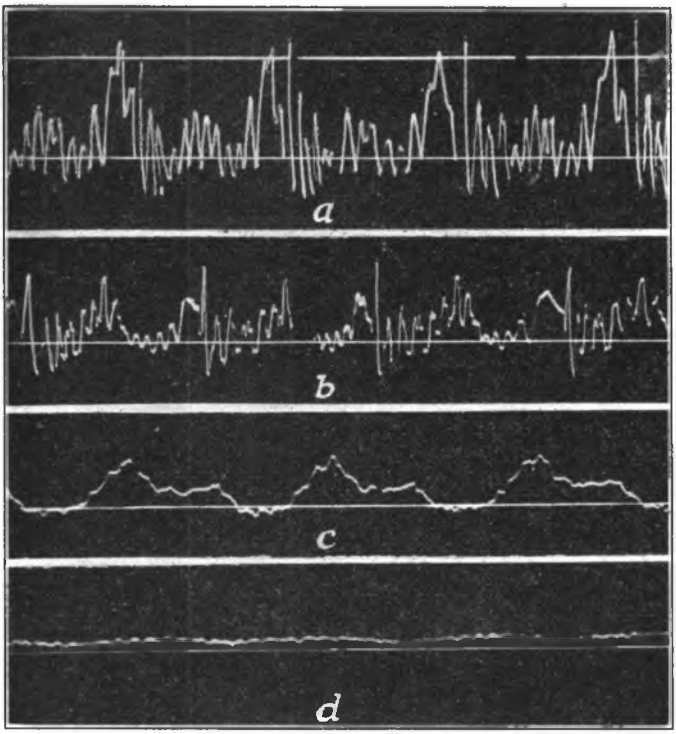

Fig. 19 Showing Quieting Effect of Pulsating Bag

(*a*) 54 ft. below compressor; maximum pulsation in line.
(*b*) 54 ft. below compressor; pulsating bag attached to quiet pulsations.
(*c*) 88 ft. below compressor; shows slight quieting effect of the 12-in. volume.
(*d*) 117 ft. below compressor; shows complete quieting effect of the 24-in. volume.

The error in velocity varies as the square root of the error in head reading. The manometer readings at the meter were corrected to a standard orifice head reading of 0.9 in., by direct proportion.

57 *Modification of Manometer Connections at the Meter.* The first attempt to reduce the error of pulsation by this means

was by throttling the manometer connections. These connections between the meter in the line and the manometer indicating the head readings were made of heavy rubber tubing having an inside diameter of $\frac{3}{16}$ in. It has long been the practice to quiet the swinging of a pressure-gage hand by throttling the gage connections. Following out this idea, a series of " orifice plugs," see Fig. 4, were made by drilling holes of known size in small pieces of brass rod.

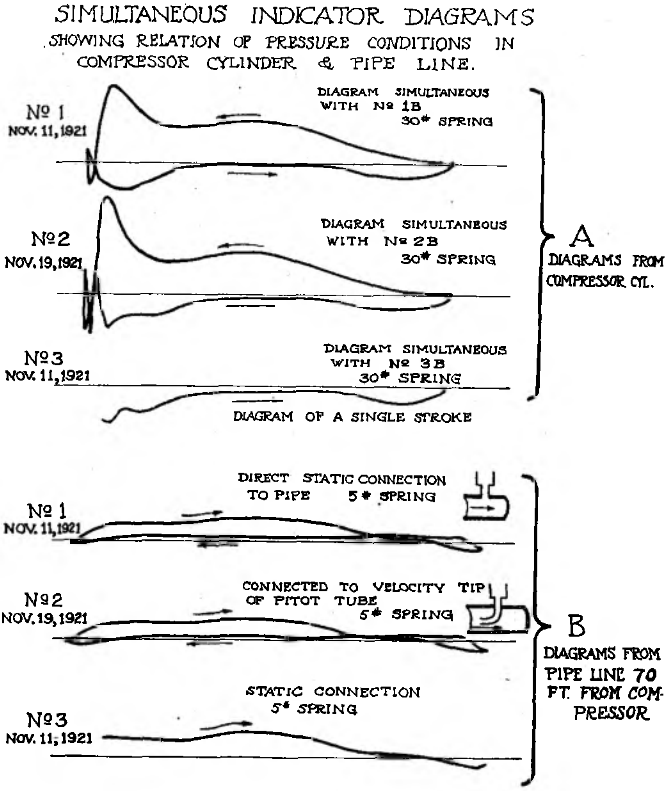

FIG. 20 SIMULTANEOUS INDICATOR DIAGRAMS

These plugs were inserted in the rubber manometer tubes both for the vertical U-tube water manometer and also for the Foxboro differential mercury gage.

58 Fig. 23 gives the average error for both these gages for maximum pulsation while using the venturi meter. The curve shows that throttling has no appreciable effect in reducing the error

until the opening has been reduced to less than 0.07 in. diameter, and that even for an obstruction so small as nearly to close the opening the percentage of error is not reduced to within practical limits. The Foxboro gage showed the same characteristic in regard to the effect of throttling, but gave an error about 60 per cent as large as that for the water manometer. In either case in order to reduce the error to 50 per cent of the maximum it would be necessary to use an orifice of 0.02 in. diameter, or the diameter of a No. 76 drill, clearly a ridiculous size. The surge, or pulsation, of the water column was completely destroyed, so that the effect is quite analogous to that of the steam gage when throttled. This indicates that while throttling a pressure gage does not affect its reading, it has no beneficial effect in reducing the error due to pulsation. That such an error might exist was pointed out by Mayo[1] in 1905, and the futility of throttling manometer connections to reduce the pulsation is also mentioned by Westcott[2] in 1922.

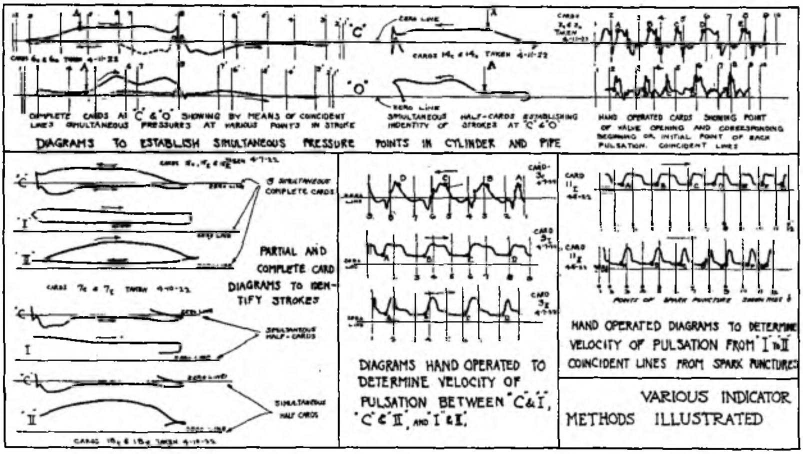

Fig. 21 Analysis of Indicator Diagrams

59 The efficient quieting effect of volumes when used in the test line suggested the possibility that small volumes inserted in the tubes leading to the manometers might serve to reduce the pulsation before the meter was reached.

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[1] Trans. Am.Soc.C.E., vol. 54, 1905, Part D, p. 502, Mayo.

[2] Measurement of Gas and Liquids by Orifice Meters, 1922, p. 143, H. P. Westcott.

60 Our first observations as to the possible effect of a volume in the manometer line were made by a comparison of the readings of the two manometers (the 6-in. inclined one-leg reservoir oil manometer and the 28-in. vertical U-tube water manometer) when used interchangeably. These two manometers when used to measure the pulsationless flow would agree exactly. When used for pulsating flow the two would not always agree, although the amount of difference between them was difficult to determine.

61 Several tests were made using the orifice meter and the 6-in. inclined gage with volumes of different sizes in one or both of the manometer connections. The results of these tests show that the use of volumes in the manometer connections does not give so favorable results as the method of throttling. There is only about 15 per cent reduction in the error for the 70 per cent orifice meter.

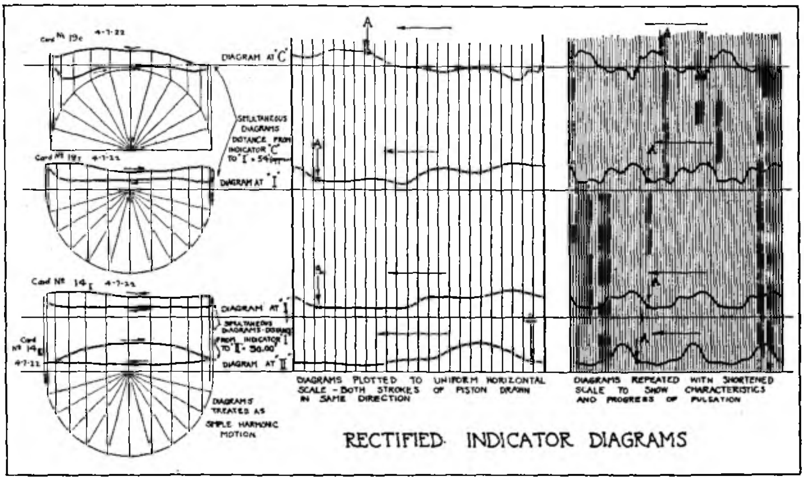

Fig. 22 Analysis of Indicator Diagrams

62 It was thought, also, that the point of attachment of the manometer connection might have some influence on the error due to pulsation. With the orifice meter comparisons were made with the manometer connected (1) close to the orifice and (2) at a distance of one pipe diameter above the orifice and at points below the orifice ranging from ½ diameter to 19 diameters.

63 Tests made show that for all orifices including the 80 per cent orifice the error at the standard points of connection is greater than that for points near the orifice which averages 96.3

per cent of the error at the standard points of connection. For points farther distant from the orifice there is a tendency for the error first to increase and then to decrease as the 19 diameters point is approaching, in all covering a total range of 20 per cent error.

64 *Effect of Type of Manometer Used.* The error in measuring pulsating flow seemed to depend to some degree upon the type of manometer used to register the head, even if all other conditions of the line and meter were identical.

TABLE 6 MAXIMUM ERROR FOR VENTURI, FLANGE NOZZLE, AND PITOT METERS

Kind of meter	Error, per cent, average
Venturi meter	82.0
1⅛ in. flange nozzle meter	76.5
1½-in. flange nozzle meter	94.3
2-in. flange nozzle meter	142.0
2½-in. flange nozzle meter	199.0
No. 1 pitot-tube meter	137.0
No. 2 pitot-tube meter	103.0

65 It may be stated that all manometers properly graduated will give the same head reading for pulsationless flow. But when the flow is pulsating, the ratio of its reading to the true reading will differ somewhat according to the variations mentioned above. A mercury manometer will probably show an error less than that of a water manometer and the latter less than one using mineral oil. A manometer with small tubes is likely to read higher than one with a larger set of tubes, but this is merely a tendency. If the

TABLE 7 MAXIMUM ERROR FOR ORIFICE METER

Size of orifice, per cent	Error, per cent, average (from curve)
33	15.0
40	25.0
50	47.5
60	81.0
70	127.0
80	185.0
90	285.0

tubes are too small the capillary effect can be noted; and if they are too large, or if they end in a reservoir, the doubtful effect due to a "volume" will be introduced. The inclined leg of a manometer under some conditions may even cause less "surge" effect. The presence of a check value or damping device between the two manometer legs or chambers, or a float to actuate the recording arm may reduce the error, as is seen in the case of the Foxboro gage.

TABLE 8 COMPARISON OF METERS

Size, per cent	Error, per cent, average	
	Orifice meter	Flange nozzle meter
37.5	20.0	76.5
50.0	47.5	94.0
66.7	112.5	142.0
83.3	207.5	199.0
	Orifice meter	Venturi meter
33.0	15.0	82.0

66 *Maximum Percentage of Error Produced by Pulsation.* For our installation the maximum error for the meters was as given in Tables 6 to 9, inclusive. The results show that the less the obstruction to the flow of the air, the greater the percentage of error due to pulsation; also, the greater the restoration of pressure after passing the meter, the greater will be the error. The reason

TABLE 9 RESTORATION OF PRESSURE AFTER PASSING METER[1]

Type of meter	Maximum error, per cent	Restoration of pressure, per cent
Venturi meter	82.0	80.0
33% orifice meter	15.0	11.5
40% orifice meter	25.0	19.0
50% orifice meter	47.0	28.0
60% orifice meter	81.0	38.0
70% orifice meter	127.0	48.0
80% orifice meter	185.0	61.0
90% orifice meter	285.0	77.0

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[1] Trans. Am.Soc.M.E., vol. 38, 1916, p. 362, 264: Water Flow through Pipe Orifices, H. Judd.

for this relation appears to be that, since the pulsation is a form of pressure energy, that type of meter unit which in itself most completely dissipates the pulsation energy will show the least percentage of error.

67 *Distribution of Pulsation as Shown by Traverse.* The pipe was traversed by both types of pitot tubes for maximum pulsation conditions. The results are shown in Fig. 24. The curves of this figure show by both traverses that error due to the pulsating flow is least at the center of the pipe. There is a slight tendency, as shown by the curves, for the point of minimum error to be located a little to one side of the center of the pipe. It is not known just how much the pitot tubes themselves are influenced by their approach to the wall of the pipe.

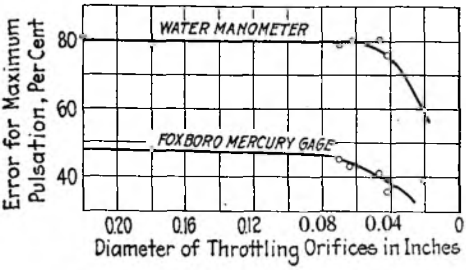

FIG. 23 EFFECT OF THROTTLING MANOMETER CONNECTIONS — FOR VENTURI METER

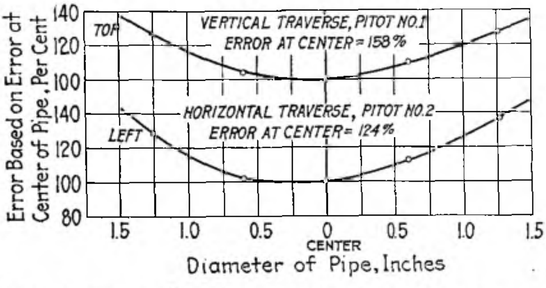

FIG. 24 DISTRIBUTION OF PULSATION ACROSS THE DIAMETER OF THE PIPE

68 *Quieting Effect of a Revolving Fan Section* (see Fig. 9, No. 7). The effect of a revolving fan section when placed in the pipe line is shown by Fig. 18. The revolving fan apparently has

some merit as a quieting device, but is of questionable practical value.

69 *Effect of the Pulsating Bag as a Quieting Device,* Fig. 6, is shown by Fig. 19. It is felt that the special design of such a device would be needed to cover the requirement of each individual installation in order to correct or eliminate the pulsating error.

70 *Elimination of Pulsation by Throttling.* The experiments carried on with the various devices for eliminating or modifying the pulsation led to the conclusion that the solution of the problem depended entirely on the absorption of the energy of the pulsation propagated as a pressure wave closely resembling a sound wave of low frequency. Whatever the device used, its value in killing the pulsation will be measured by its ability to absorb, or dissipate, this energy of pulsation.

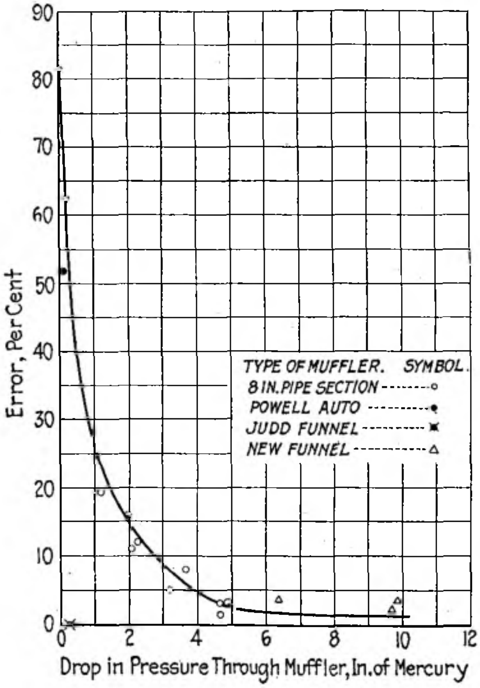

FIG. 26 EFFECT OF MUFFLERS FOR QUIETING PULSATION — USED WITH VENTURI METER

71 The first attempt made to quiet the pulsation was by means of throttling either by valve or by orifice. The loss of pres-

sure during passage through the valve or obstruction in the line was the eliminating factor.

72 The general effect of throttling is to reduce the error rapidly by means of a pressure drop up to 4 in. of mercury. The use of a greater pressure drop causes the error to be reduced more gradually. The manner of throttling is immaterial whether by gate or globe valve or by an orifice.

73 The general characteristics are summarized in Table 10. This table shows that a drop in pressure of 4 in. by throttling is needed to make an appreciable reduction in the error; and a drop of 6 in. or 3 lb. per sq. in. is necessary to bring the error within practical limits. In most cases the error is not reducible below 1 to 3 per cent, even with a sacrifice of a drop of 12 in. mercury.

TABLE 10 ELIMINATION OF THE PULSATION ERROR BY THROTTLING

Kind of meter used	Drop in pressure by throttling, inches of mercury				
	0	2	4	9	12
	Error, per cent				
Venturi	82.0	26.0	10.0	5.0	2.5
33% orifice	10.0	2.0	0.0	0.0	0.0
50% orifice	58.0	17.0	7.0	4.0	2.0
70% orifice	145.0	50.0	18.0	9.0	4.0
80% orifice	175.0	67.0	25.0	12.0	4.0
90% orifice	315.0	118.0	22.0	–5.0	18.0
1⅛-in. flange nozzle	44.0	18.0	8.0	3.5	1.0
1½-in. flange nozzle	83.0	28.0	10.0	5.0	1.0
2-in. flange nozzle	156.0	50.0	16.0	6.0	1.0
2½-in. flange nozzle	340.0	97.0	31.0	7.5	1.0
Pitot No. 1	160.0	50.0	20.0	–7.0	2.5
Pitot No. 2	140.0	81 0	5.0	0.0	3.5

74 *Elimination of Pulsation by the Use of Volumes.* Tanks, or volume capacities, or "volumes," as we have chosen to call them, were used in the line for the purpose of quieting the pulsation. These volumes were inserted in the line so that the direction of flow through them was along the axis of the volume. The connections were made by means of pipe flanges; and later orifices were inserted in these flanges at the entrance and exit of each volume. This produced an abrupt entrance into and an abrupt exit out of the volumes, which in itself would tend to cause a loss of energy; and hence would probably contribute toward the reduction of the energy imparted to the pulsation. These volumes were all cylin-

drical in shape and with the exception of the 8-in. and the 48-in. volumes were made of thin sheet metal, No. 24 gage.

75 The quieting effect due to the use of volumes is shown by the curve sheet in Fig. 25. The dotted curve is drawn in as a representative average curve for both venturi and orifice meters where volumes, alone, are used.

76 The 24-in. volume in our test line, situated below the meter, had a capacity of 29 cu. ft., and was plainly one of ample size to convert the pulsating flow into pulsationless flow when the air reached the line leading to the orifice head. It is evident from these results that a volume is also a practical means of eliminating the pulsation. The chief question is, whether in large installations volumes of sufficient size would be of practical use.

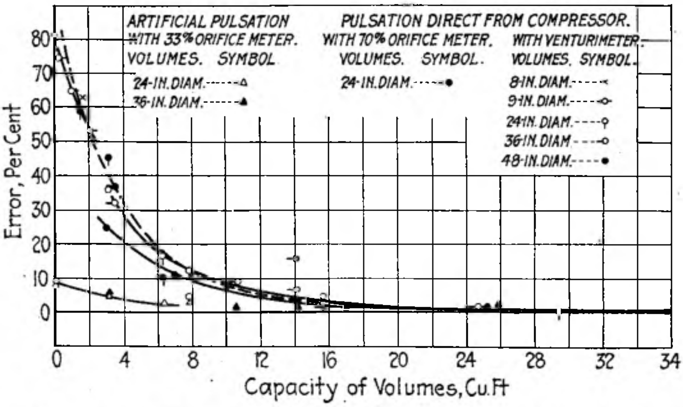

FIG. 25 PERCENTAGE OF ERROR FOR VENTURI AND ORIFICE METERS — PULSATION QUIETED BY VOLUMES

77 *Effect of Varying the Shape of Volume* was also studied. In a general way a volume is probably more efficient when it is of relatively large diameter.

78 *Elimination of Pulsation by Combining Throttling with Volumes.* Since the pulsation could be nearly if not quite eliminated either by the use of throttling devices or by the use of volumes alone, the natural conclusion was that some combination of the two schemes might be discovered which would give satisfactory results without the objectionable large pressure drop or the excessive size of the volume. A series of runs was made, while the various volumes were in the line, where orifices of various sizes were placed

at the entrance and exit of the volumes. The venturi and the orifice meters were used in these tests. It was found that it was possible with a volume of several cubic feet, combined with a pressure drop of about two inches of mercury, to reduce the error to a small figure, even for a meter having a large maximum error.

79 *The Muffler as a Quieting Device.* Following the experiments with the volumes and orifices combined as a means of eliminating the pulsation, the idea was further developed by the combination of a volume with several orifices; or in other words, the adaptation of the principle of the automobile muffler to the problem of pulsating flow.

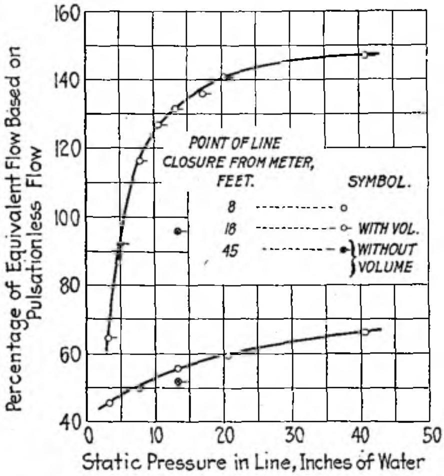

FIG. 27 EFFECT OF PULSATION ON VENTURI METER IN "DEAD-END" LINE

80 To study the effects of a muffler a device was constructed of 8-in. pipe-flange sections, as in *B,* Fig. 8. The curve given in Fig. 26 is based upon all the results obtained for every type of muffler tested. The results for the 8-section muffler were more complete and show at the upper limit an error of 81.5 per cent for pulsating flow for open pipe. The whole curve shows that the effectiveness of any single type of muffler, aside from its value as a volume alone, depends entirely upon the amount of throttling produced and very little upon the design and arrangement of its baffle work.

POSSIBILITY OF ADJUSTMENT OF ERRORS

81 There is a possibility that the error shown by a meter when measuring pulsating flow may be so adjusted or so compensated for, that the true quantity passing through the meter may be known. This is mentioned as a possibility only, and forms a basis for comments on some of the circumstances which would attend such an attempt.

82 There is the first possibility of the integration of the curve, obtained by means of the photopulsometer, which is a series of velocity-time diagrams. The second possibility would be the use of a correction factor for the manometer itself. A third possibility would be the determination of a pulsating factor by calibration under actual running conditions.

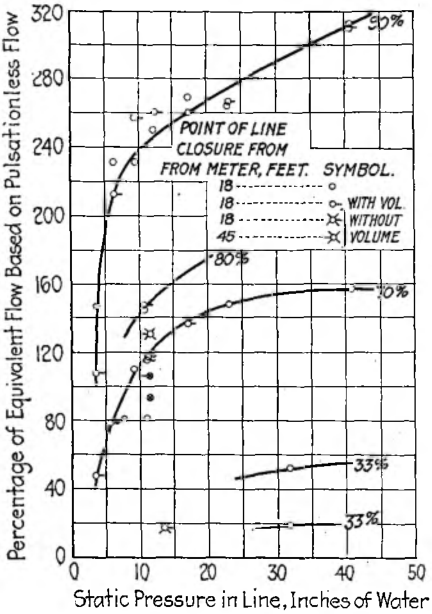

Fig. 28 Effect of Pulsation on Orifice Meter in "Dead-End" Line

83 *Effect Produced by "Dead-End" Pulsation.* During our experiments in connection with the effect of pulsations on the static pressure we had noticed indications of a reading on the meter for zero velocity in the line. Later a series of tests was made with each of the four meters in while the test line was closed at different points

beyond the meter station. The static pressure, at a point in the line 6 ft. above the meter, was maintained the same as during the regular line of tests for 0.9 in. static head at the orifice head. This static pressure was secured by regulating a by-pass valve in the line 18 ft. above the meter (see Fig. 10). The line could also be closed at flanges located at 8 ft., 18 ft., 40 ft., and at the orifice head, 45 ft. below the meter. For the " dead-end " tests most of the runs were made with the large tank, *T*, in the line, and a few runs were made with the large tank out of the line.

84 The effect produced by the " dead-end " pulsation is represented by the flow equivalent to the reading on the meter as compared with the flow under pulsationless-flow conditions. The curves shown in Figs. 27–31 show this relation for the four types of meters. The standard flow conditions as represented, during the regular runs, by the 0.9 in. static head at the orifice head, the static pressure in the line above the meter would read about 9.5 in. of water for pulsationless flow and the corresponding static head under pulsating flow would range from 9.5 in. to 16 in. of water, according to the type of meter used. Generally speaking, as would be expected, the static pressure in the line read a little higher under pulsating flow than under pulsationless flow, in some cases showing an increase of 3.5 in. in 10 in. This would be equal to an error of 16 per cent due to pulsation.

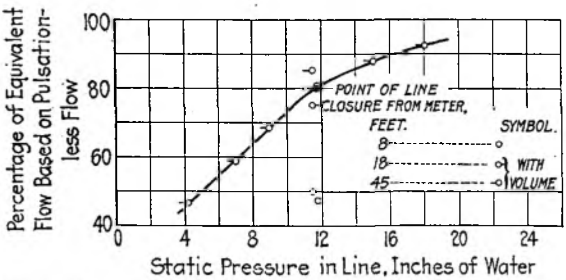

Fig. 29 Effect of Pulsation on 1½-in. Flange-Nozzle Meter in " Dead-End " Line

85 The curves, Figs. 27–31, give, especially, the effect due to change in static pressure in the line while the meters are in a " dead-end " line. For all meters there is an increase in pulsating effect as the static end is increased up to 20 in., after which they increase more gradually up to 40 in. static pressure, the limit of the tests.

86 In most cases there was a tendency toward an increase in the false flow reading with increase of distance to point of line closure from the meter. In two instances the meter showed a negative reading. The rapid change in this effect on the meter with variation in static pressure, together with the marked variation in apparent flow with change in point of line closure from the meter, makes it exceedingly doubtful whether any reliability could be placed on this method of obtaining the pulsation factor for any given installation.

87 *Application of Proposed Formula to Pulsating Flow.* An attempt has been made to test the relation expressed by the following formula by means of the "dead-end" flow data. This formula[1] is: $P_2/(\sqrt{P_1} \pm \sqrt{D})^2 \times 100 = 100$ per cent, where P_1, P_2 and D are respectively the corrected manometer readings for pulsationless flow, pulsating flow, and "dead-end" flow. The positive value of D has been used since it was considered to be better adapted to the data taken.

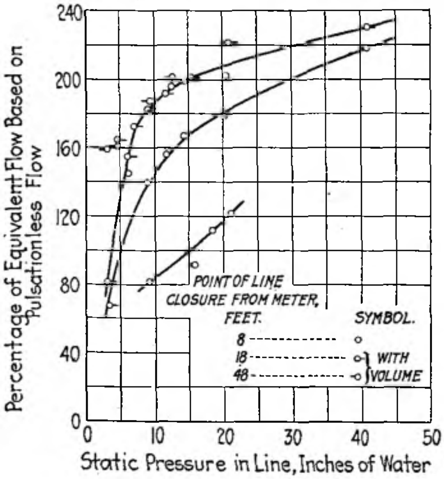

FIG. 30 EFFECT OF PULSATION ON PITOT TUBE NO. 1 IN "DEAD-END" LINE

88 Fig. 32 shows the relation between the ratio P_2 to $(\sqrt{P_1} \pm \sqrt{D})^2$ and the point of line closure. The curve in broken lines is the average for the total number of results; the full line is the average for the few points for the line without the volume, Q. For the 8-ft. distance the results are widely scattered and indicate

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[1] Measurement of Gas and Liquids by Orifice Meter, H. P. Westcott, 1922.

that this distance is too close to the meter. The 18-ft. distance gives results showing more uniformity with the average close to 100 per cent. This would indicate the formula would apply better for line closure at 18 ft. The 45-ft. point, though representing the end of the duplicate line, with an average ratio falling below 100 per cent, would indicate less agreement with the formula. The volume Q does not make any marked effect, or as much effect as is shown by difference in length of line closure from the meter.

89 The uncertainty as to where the point of closure should be made or as to whether a length of line duplicating any given line would give the true pulsating-head factor make it doubtful whether the proposed formula could be applied with any assurance of a reasonable degree of accuracy.

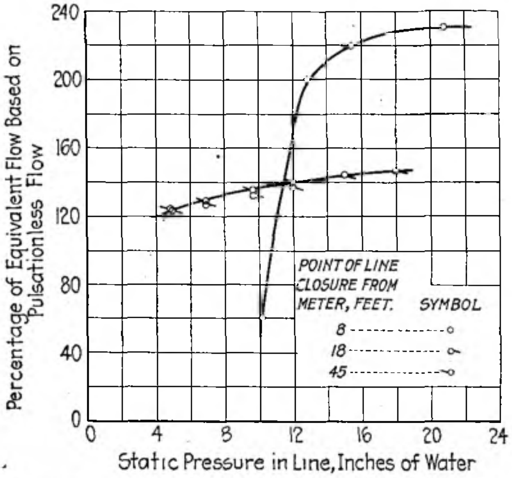

FIG. 31 EFFECT OF PULSATION ON PITOT TUBE NO. 2 IN "DEAD-END" LINE

CONCLUSIONS

90 This investigation relating to our special installation is summarized as follows:

A Nature of Pulsations:

a Pulsations in a pipe line, originating from a reciprocating piston, or a similarly disturbing system, consist of sudden changes both in the velocity and in the pressure of the fluid.

b The pressure change is the most apparent and is probably the greatest factor in producing errors in metering devices.

c The pressure change is in the form of a wave front resembling a traveling sound wave of low frequency.

d The pressure wave travels in the pipe with the velocity of sound.

e The velocity of the pulsation is independent of the velocity, or quantity, of fluid flowing.

f Pulsations in air flow are similar to the compression waves set up by water hammer. Both travel at the velocity of sound in the fluid and are independent of the velocity of flow.

g The effect of this pulsation on a flow meter is to increase its reading, often causing an error of great magnitude. The magnitude of this error depends upon the frequency of pulsation, nominal static pressure of the fluid, type of meter used and adjacent fixtures in the pipe line.

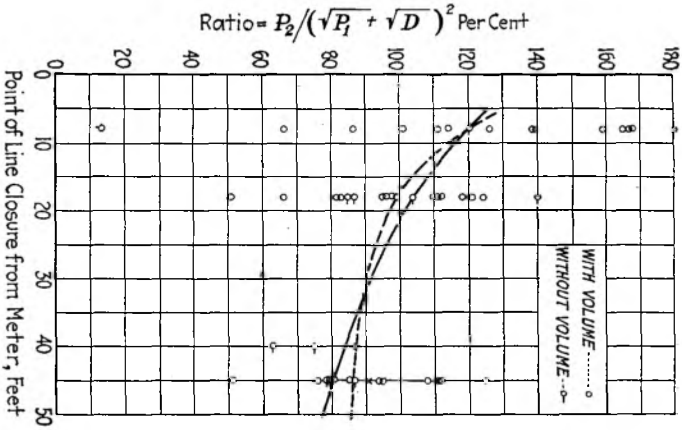

Fig. 32 Effect of Line Closure on Proposed Formula — with "Dead-End" Pulsations

h With orifice meters and flange nozzle meters the pulsating error increases as the diameter of the orifice, or nozzle, approaches the diameter of the pipe.

i The throttling or modification of the manometer connections to the meter does not appreciably reduce the error.

j The point of attachment of manometer connection has no great effect on the error due to pulsating flow.

k The pulsation error at the center of the pipe is 35 per cent less than that at the wall of the pipe.

l A meter on a "dead-end" connection will usually show a positive error of considerable magnitude.

m The pulsation must be eliminated or greatly reduced in order to have the meter read without objectionable error.

B Practical Elimination of Pulsations:

n Because of the high velocity of the pulsation, an excessive length of pipe line would be necessary to destroy the pulsation.

o Throttling is effective but requires a pressure drop of 6 in. of mercury to reduce the error to 5 per cent.

p Abrupt volume enlargements in the pipe line will eliminate the error, if of sufficient capacity. A volume capacity of 20 cu. ft. is required for an error within 2 per cent.

q Generally speaking, for the same capacity, a volume of relatively large diameter is more effective than one of small diameter.

r No relation was found between the compressor displacement and the capacity of the volume chambers.

s The combination of throttling with volumes forming the "muffler" device probably is the most effective device for the mechanical elimination of pulsations.

t The pulsating bag, or diaphragm, and the fan, or revolving baffles, are partially successful in eliminating the pulsations, but their installation is thought to offer serious practical objections.

u The effectiveness of any of these quieting devices seems to depend upon their ability to dissipate or change the energy of pulsation which is effected chiefly through a drop in pressure.

v The device which will destroy the pulsating energy with the least obstruction to the flow of the fluid is the most desirable.

w The effectiveness of the meter element itself in quieting the pulsation depends upon the degree of restoration of the pressure beyond the meter. The greater the percentage of restoration, the higher the percentage of error shown for any given type of meter.

C Adjustment of Error of Pulsation:

x It is probably not feasible to correct any meter by means of a correction factor owing to the disturbing effects which may arise from slight changes in the installation and running conditions.

y The experimental establishment of a pulsating correction factor and its relation as shown in the proposed formula is not considered feasible with our present experimental knowledge of the laws of pulsating flow.

z It seems probable that each installation where pulsating flow is present would present its own peculiar problem for which an individual study and consideration of the existing conditions would be necessary for a satisfactory solution.

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Trans. Am.Soc.M.E., vol. 38, 1916, pp. 362–364: Water Flow through Pipe Orifices, H. Judd.

DISCUSSION

H. N. Packard. We do not agree that the "pressure change . . . is the greatest factor in producing errors in metering devices." For instance, imagine a compressor cylinder discharging through a short length of pipe, in which is mounted a pitot tube, into a large volume such as a gasometer. In the pipe section no measurable static pressure change during the cylinder discharge can be detected, but a very appreciable variation in rate of flow must occur with the consequent error of meter reading. This is readily confirmed by actual test with the pitot tube. As a further proof of this point, in the Thomas meter, which is entirely independent of pressure conditions and indicates only the standard units flowing through it, we have errors with heavily pulsating flows. Assuming a pulsating flow of sine wave form, the meter error is negligible up to the point where the flow at the peak of the wave does not vary more than 30 per cent from the mean rate. When the wave amplitude is as great as the mean flow, giving instantaneous stoppage of flow in each cycle, the meter error reaches a maximum of nearly 8 per cent. As practically all meter installations are fairly close to the pulsation producing piston, we believe the errors are mostly due to actual instantaneous flow variations through the metering device.

We believe that the velocity of transmission of the wave is that of sound plus that of the gas velocity, slightly modified by the size and shape of the pipe line. We have found a number of references in standard works on physics that the velocity of sound in air is dependent on the wind velocity as well as the density of the air. Do the authors feel that their data can support their statement? Their maximum test velocity was 27 ft. per sec. compared with about 1100 ft. per sec. for sound, and it seemed to us difficult to be sure that the experimental error was not as great as this.

The curves on Fig. 23 would indicate some reduction in manometer error with throttling of connections. Have the authors any explanation of this other than possible leaks? We can see no other reason for the gain in accuracy.

The statement is made that at least a 6-in. mercury pressure drop is required to reduce pulsations to a practical limit. Do the authors consider this a general statement or applicable only to their test conditions? It would appear to me to be a function of the density of the fluid, its velocity and the pulsation wave form (magnitude of pulsation) if made as a general statement.

We are still of the opinion that there is some relation between the piston displacement and volume of a quieting receiver which will give good results. Taking the two absurd extremes of a volume equal to piston displacement and an infinite volume, in one case we know that no effect will be produced and in the other perfect quieting of pulsations will occur. We believe that the quantity of fluid discharged per stroke, the number of strokes per minute and the volume and diameter between the source of pulsations and the meter determine the pulsation effect at the meter, at least with elastic media such as gases.

On dead-end error tests we believe that there is an actual displacement of gas back and forth in the meter, this flow effect being due to the elasticity of the gas which is alternately compressed and expanded in the dead-end volume. In our own meter the dead-end effect does not occur at all except with such large dead-end volume that the alternate gas flows through it, traveling at least seven inches in a reverse direction. This condition has been met but once in our commercial experience. Our meters are normally set vertically with the normal flow vertically upward. At zero load a very small amount of heat is still left in the heater to maintain control and due to convection current the heated gas rises through the exit thermometer and maintains its temperature higher than the entrance thermometer sufficiently to give a constant tendency to shut down the meter. With large dead-end volume and severe pulsations there is sufficient back flow to overcome the convection currents and carry heated gas from the heater into the entrance thermometer, increasing its temperature to approximately the same as the exit thermometer. Immediately the control for the meter goes to full load under such conditions.

J. M. Spitzglass. Prior to the advance of Professor Judd's experimental work on pulsating flow there was an idea prevalent that the error in the measurement was due mainly to the magnifying effect of the differential column, reading the average height and the corresponding square root of this average instead of the average of the instantaneous square roots which are the equivalent of the varying flow.

With the development of the flow meter, we sought to eliminate this error by making the meter respond electrically to the instantaneous instead of the average height of the differential column. This provision was thought to eliminate the part of the error which the authors of the paper designate as the "effect of the type of manometer used." We soon discovered that there was a much larger error due to the "harmonic" effect of the pulsations in the flow. Still, in all our observations with reciprocating flow this error seldom exceeded 25 per cent under any circumstances. Furthermore, this error could be easily eliminated by moderate restrictions in the form of additional orifice plates on either side of the differential medium.

The writer was greatly surprised when he first glanced at the tables in the paper to note that the errors in some of the meters were as high as 200 per cent and over. The writer does not for a moment cast any doubt on the data of the given observations, but he has felt from the beginning that there must be something misleading in the algebraic presentation of the results. After reading the paper a second and third time, the solution of the riddle presented itself very clearly.

In summarizing the tabular results of the investigation, the authors adopted the velocity pressure of the flow as *the* basis for comparing the effect of the pressure pulsations, which, according to their own explanations and results, was not in the least a function of that velocity pressure. What they actually did was to compare a variable quantity, the pressure pulsations, on the basis of another and more variable quantity, the velocity pressure of the flow in the given meter. It will be observed, therefore, that whenever the assumed basis, the velocity pressure of the meter, decreased, the apparent percentage of error increased in a corresponding ratio.

The writer believes that this is the real reason why the percentage of error increased when the size of the orifice or the flange nozzle was increased. The same reasoning applies and is a sufficient explanation for the fact that the percentage error increased in the case of the pitot tube at the wall of the pipe, where the velocity pressure (the assumed basis) is the lowest. Furthermore, the dead-end phenomenon shows conclusively that the effect of pulsation is not a factor of the velocity pressure of the air.

As the data and the results of the investigation are exceedingly important for the users of the meter on pulsating flow, the writer would like to ask the authors to include in the paper a summary table, similar to Table 4, giving the actual values of the static pressure in the line, the actual velocity pressure, and the difference in static pressure between the pulsating and pulsationless flow for all meters tested. It can be readily seen that if the difference has a value of, say, 5-in. of water, it may form a square-root error of 145 per cent on a meter whose velocity pressure is only one inch of water, while the same 5-in. difference will form an error of only 5 per cent on a meter whose velocity pressure amounts to 50-in. of water; and what is more important, if by means of moderate restriction or increased volume the difference is reduced from 5 to 0.5 in., it will still give an error of 22 per cent in the first case and will be entirely insignificant in the second case. To state this in another way: The effect of pulsation, according to the writer's understanding of the investigation, is shown to be rather in the nature of an additional term than a factor in the algebraic expression of the flow for a given meter.

R. J. S. Pigott. The paper on pulsating flow reports the results of research work undertaken for the Special Committee on Fluid Meters, of the Society's Research Committee.

One point about pulsating flow seems to be coming more strongly to the fore; that is, the problem is largely an acoustic one. All the data go to show that the variability of the conditions is due to the fact that the acoustic conditions in the pipe differ with every installation, and it is hard to see how pulsating flow can be stopped in every case until a study is made of the phenomena from an acoustic standpoint.

Up to the present time we have not developed devices for detecting the acoustic variations. We have been working along lines of mechanical devices almost wholly, and have never given enough attention, as yet, to demonstrating clearly what are the acoustic conditions in the pipes.

One of the earliest problems in the opinion of the members of the Fluid Meters Committee was that of either providing correction for the effect of pulsating flow upon the indications yielded by the flow meter mechanism, or to so reduce the pulsations as to render their effect insignificant. The net result of research has definitely confirmed the belief that any type of meter operating on a difference of head which is proportioned to the square of velocity will register high on pulsating flow. The other belief, that it is very difficult, if not impossible, to provide suitable correction factors for the readings of the meter, is also very largely confirmed. The problem, therefore, is mainly reduced to providing commercially practicable means for suppressing pulsations to a point where they do not have a marked effect in the registration of the meter.

The experimental work so far carried out has indicated that it is feasible to accomplish this end by means of a combination of throttling with enlargement of volume. The scope of the experimental work has not been large enough as yet to definitely establish the amount of throttling and the amount of volume enlargement required for any particular case and it is probable that the variations in velocity and size of lines will render an exact solution for any specific case difficult. However, there is a good deal of encouragement to be drawn from the evidence that in all likelihood proper relations of the two requirements can be determined to cover a considerable variation in pulsation condition. The situation on pulsating flow is only one factor of several which have tended to reduce the reliance placed upon flow meters for accurate measurements, and it is not generally recognized that the inaccuracies found in the commercial operation of flow meters are due almost entirely to the conditions under which the flow meter is installed. Under proper installation conditions, it can be demonstrated that any well designed flow meter can give results with perfectly satisfactory precision. However, in the great majority of installations insufficient attention is given to the effect of pulsating flow, eddy currents in the lines due to valves, elbows or similar obstructions and leakage in the lines, transmitting a pressure difference to the meter indicating and recording mechanism.

The first report of the Fluid Meters Committee was to have been produced for the Annual Meeting but the amount of work to be done both in editing the report and preparing for printing was too much to permit publication at this time.

This report will cover the matter of installation very fully as well as the theory and accuracy of the devices employed. It is to be hoped that this report will provide for the designers and users of flow meters a complete summary of information available on the subject. Hitherto there has been no single source from which this information could be obtained and it has been scattered through three or four hundred different publications.

John L. Hodgson.[1] In the opinion of the writer, the results obtained from the elaborate researches described in the paper might have been very much greater had a careful analysis been made beforehand of the ways in which pulsating flows cause errors in meters which are based upon the measurement of a differential pressure.

By making such an analysis the writer has found it possible to reach wider and more general conclusions than the authors of the present paper at the expense of far less experimental work.

Some of the most important of these conclusions are summarized below.

A pulsating air flow may be considered to consist of:

a A "pressure variation" which is transmitted with the velocity of the fluid in the pipe, plus the velocity of the sound in the fluid proper to the particular size and roughness of pipe used, and the nearness to the source of pulsation of the point where the velocity is measured.

b A "velocity variation" during which the whole of the air in the pipe is accelerated or retarded.

The fluid at a point distant from the source of pulsation does not however change its velocity until the impulse, transmitted with the velocity stated under *a* reaches it.[2]

Both these pressure and velocity variations cause errors[3] in the meter; but in quite different ways.

The error due to the pressure variation occurs when the pressure pipes leading to the meter have different coefficients of discharge for inflows and outflows, and when the capacity in the meter on the two sides of the water or mercury column are different.[4] It is then

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[1] Eggington House, Beds, England.

[2] The authors state that the velocity of propagation of the impulse is that of sound. That may *apparently* be so in the case of their particular experiments; as the effect of the pipe walls is to retard the speed, and of the moving air to increase it.

[3] The above sources of error, and also the effects of "square root" and "viscous" damping of the manometer or meter were pointed out in a paper by the writer in 1916; see *Proc.* Inst. C. E., vol. CCIV, p. 134 to 137.

[4] In the case of the photo-pulsometer, shown in Fig. 11, the upstream

possible to obtain an actual difference of pressure on the two sides of the meter by the pressure variation alone and when there is no velocity variation at all in the pipe.[1]

The error due to the pressure variation[2] may easily be brought down to a very small amount by using pressure connections which have equal coefficients of discharge in both directions, and by keeping the capacities in the meter about equal.

There remains the error due to velocity variation, which is the real source of trouble.

This causes error because the flow depends upon the mean of the square root of the pressure differences across the measuring device; whereas the meter reading[3] depends (approximately)[4] upon the mean of the pressure differences.

It can be shown by calculation that for certain wave forms this "velocity variation" may produce errors of several hundred per cent.

The error due to this cause can be calculated or determined by calibration for any particular conditions; but as it varies with the rate of flow, and the wave form, and the product of the specific volume and the absolute pressure of the fluid, and the loss of pressure in, and the capacity of, the pipe line, it is best reduced to a small amount rather than allowed for.

The only way to reduce it is to smooth out the wave form of the "velocity variation" at the metering point.

This can be done in many ways, the simplest of which (not mentioned by the authors) is to insert a capacity *and* a throttling

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cavity is larger than the downstream cavity, with the result that when a change of pressure occurs the pressure will rise and fall most quickly in the downstream cavity; thus exaggerating all the readings. Many of the diagrams taken with this instrument indicate negative flows (instead of the positive flows which must actually have existed) because of this defect.

[1] The "dead end" condition referred to by the authors.

[2] The "pressure change" is wrongly stated by the authors to be "probably the greatest factor in producing errors." The "pressure change" is more rightly considered as a "symptom" than a "cause."

[3] That is, assuming that the meter is adjusted so as to show no appreciable error due to the "pressure variation."

[4] This is only true when the "damping" in the pressure pipes and the meter follows the "viscous" law. If it follows the "square-root" law the mean meter reading is not the true mean of the pressure differences. This may explain the change of manometer error as the pressure pipes are throttled shown in the authors' Fig. 23. The data given in the paper are, however, insufficient to enable the point to be settled.

device between the source of pulsation and the metering point. If the meter itself offers sufficient resistance it may form the throttling device; if it does not, an additional throttling device may be added. The capacity should be placed between the source of pulsation and the meter, and the additional throttling device, if any, should be placed on the downstream side of the meter. (See Fig. 33.).

In a paper read before the Midland Institute of Mining, Civil and Mechanical Engineers in January 1921, and again in a paper read before the Institute of Naval Architects in April 1922, the writer showed that, if certain assumptions were made in order to simplify the reasoning[1], it could be proved[2] that the percentage error of a meter for any particular wave form depended upon the value of the ratio:

$$FCL/ZQ$$

where F is the frequency with which the wave form repeats itself

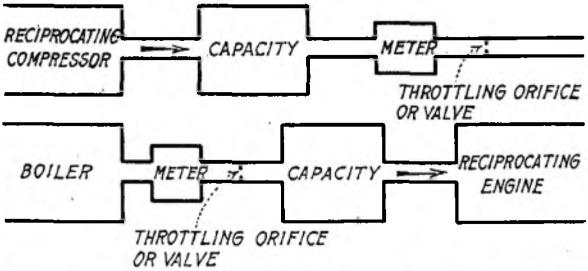

FIG. 33 LOCATION OF CAPACITY WITH RESPECT TO SOURCE OF PULSATION AND METER

C is the capacity, and

L is the loss of pressure between the entrance to the capacity C and the side of the metering device which is furthest from the source of pulsation

Z is the product of the specific volume of the fluid and its absolute pressure

Q is the rate of weight flow.

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[1] Such as that the meter is adjusted so that the "pressure variation" causes no error; that the only error is caused by the meter taking the mean of the pressure differences across the measuring device, instead of the mean of the square root of the pressure differences; that L varies in Q^2, etc.

[2] For an elementary proof, see the writer's paper published in the *Proc.*, Inst. Naval Architects, April 1922.

The writer has developed methods which enable curves connecting the values of *FCL/ZQ* and the per cent error of the meter due to the "velocity variation" to be calculated and drawn out, so that, given the wave form, and the values of *FZQ*, the value of *CL* which will reduce the pulsation error to small limits can be immediately read off.

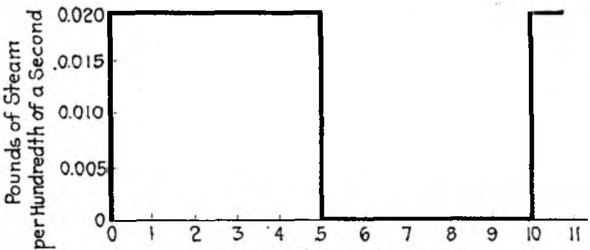

FIG. 34 SQUARE WAVE FORM

Such a curve for a square wave form, Fig. 34, is shown in Fig. 35.[1]

Many interesting results follow from the *FCL/ZQ* relation, among which are:

1 A large meter error may often be reduced to a negligible amount by trebling or quadrupling the value of *CL* by providing for additional throttling and by putting the meter further from the source of pulsation so as to secure additional capacity. It will be seen that in order to reduce the pulsation error, it is equally efficacious to

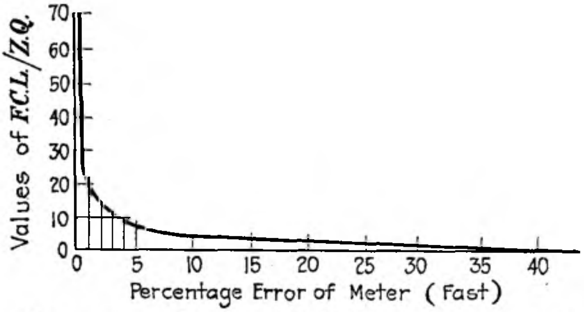

FIG. 35 RELATION OF VALUES OF *FCL/ZQ* AND PER CENT OF ERROR OF METER

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[1] Compare the authors' Fig. 26, which is plotted against *L* only.

increase C or L. The energy lost is, however, least when the pulsation is reduced by increasing C.

2 If the rate of flow is reduced on account of the compressor slowing down (the wave form remaining the same) the meter error will be increased, as F and L are reduced, and L falls off more rapidly than Q.

3 Similarly when a steam engine governs, the meter error increases as the flow is reduced. The increase in the error is greatest when the engine governs on the "cut off" (instead of "on the throttle"), as the wave form is then altered for the worse. If there is an appreciable steam chest capacity on the engine side of the throttle, the pulsation error may actually be reduced when the engine governs "on the throttle."

4 If the throttling orifice shown in Fig. 33 consists of a valve (instead of a fixed orifice) and this valve is shut down (either automatically or by hand) as the flow is reduced so that the original L is maintained, the pulsation error will remain constant at all flows, if F and Q fall off in the same ratio.

5 It will be seen on reference to Fig. 35 that if the pulsation error is large, any small change in the value of FCL/ZQ will cause a large change in the pulsation error, whereas if the pulsation error is reduced to 1 or 2 per cent there may be large variations in the value of FCL/ZQ without causing any appreciable change in the overall error of the meter. It is therefore far better to reduce the pulsation error to a small amount by increasing FCL/ZQ than it is to "rate" the meter by actual calibration for a large pulsation error.[1]

6 The FCL/ZQ relation explains the authors' conclusions $A(h)$ and $B(w)$, since it shows that the pulsation error is large when L is small.

7 It can be shown that for given values of FLZ and Q the amount that the meter reads fast is (roughly) inversely proportional to C^2, or for given values of CLZ and Q to F^2 and so on.

It should be understood that the FCL/ZQ relation, being deduced from premises which simplify the actual conditions, does

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[1] Compare the authors' conclusions $A(m)$ and $C(x)$.

not hold with absolute rigidity in practice, and also that it only holds over a limited range of conditions.[1] At the same time it serves as a most valuable key to the meaning of what is otherwise a mass of unrelated data.

The writer would say that he disagrees with the authors' conclusions $A(b)(d)(e)(f)(i)$, and $B(n)$.

It will be seen that he is generally in agreement with conclusions $C(x)$ and $C(z)$. With regard to the latter he would say that curves connecting the values of CFL/ZQ and the percentage error of the meter which he has had calculated out enable his firm (Messrs. Geo. Kent of London and Luton, England) to decide on the proper value of CL for any particular case at the expenditure of a few minutes' work only.

In conclusion he would like to congratulate the authors upon the scope of their work, and upon the clear way in which they have set forth their results.

The Authors. In reply to Mr. Packard, we can readily see that his type of meter would not be greatly affected, if any, by the pressure changes, even though the static pressure gage might read higher due to the pulsation. We would also conclude from our investigation that his meter would be less affected by the pulsation because the effect on the velocity head seems to show much less error than that produced in meters depending on the pressure drop readings.

In regard to the effect produced by the static pulsation we have failed to convey the proper meaning. The change or effect on static pressure produced by the pulsation is much greater than the effect produced on the velocity head. This pulsation, like sound, seems to be propagated as a pressure wave and the effect produced on any measuring device, especially where difference in pressure head is used, is much greater than the effect recorded on the velocity diagrams from the photo-pulsometer. Hence, the conclusion that the "pressure change" was the greatest disturbing factor was drawn. This we believe to be borne out in our work. By the photo-pulsometer the diagrams with air flow through the venturi showed a maximum velocity change of $1\frac{1}{2}$ in. = 4.5 in. water as taken with the pitot tips which from their construction would produce a magnified reading while for the same flow con-

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[1] For instance, it does not hold when the rate of flow is so great that the loss of pressure, L, no longer follows the square root law.

ditions, the indicator diagrams giving static pressure fluctuations showed a change about 1.2 lb. or say 35-in. water or about eight times as great as was shown in the velocity head reading neglecting the fact that the instrument gave a magnified reading.

Furthermore in Fig. 20, the diagrams 1 and 2, section B, show a pressure card and a pressure and velocity head card respectively. A comparison of the two cards show little or no difference and at least indicate no great change, if any, due to the velocity head when added to the static head, as taken by a pitot tip attached to the indicator cock.

It seems apparent, therefore, that the pulsation, (assuming its propagation as a pressure wave) is transmitted in the pipe by means of the air (either flowing or quiet) as a medium; and that with the dead-end meter connection the pulsation is surging back and forth independent of the air which itself may also have some slight movement back and forth. This transmission of pulsation in the dead-end line would seem to be similar in this respect to the surge of pressure in a water line due to water hammer which is very much greater in magnitude as compared with the effect due to velocity.

In regard to the velocity of the pulsations, the statement should be modified to show that the velocity of the pulsation included the velocity of the wave and the velocity of the air. For the maximum velocity of 27 ft. per sec. the error would be less than 3 per cent if we neglect the velocity of the air which of course is much less than the actual experimental error.

The conclusions given in the summary are made with reference to the installation which we tested; also reference to the throttling effects of a six-inch mercury pressure drop considers our test conditions only, and should be modified much according to Mr. Packard's suggestion.

In regard to error due to throttling manometer connections, we do not believe that there were any leaks, since these manometer throttling plugs were made up in sets all of the same material and in the same way, and furthermore the data seemed to be consistent.

Referring to the relation to piston displacement of the volume of a quieting cylinder, it is probably true that *some relation* exists, but it seemed to us that it would take such an extended investigation to establish anything approaching a law, as to render the solution impracticable.

In the dead-end meter installation, we agree with Mr. Packard that there is an actual forward and back flow of the fluid due to the elasticity of the gas; but it is also true, we think, that the pulsation in the form of the compression wave travels forward in undiminished amplitude and returns in more or less diminished amplitude depending on the length, shape, and volume of the dead-end connection.

Mr. Spitzglass states in his discussion that the authors in finding the per cent of error due to pulsating flow have compared "a variable quantity, the pressure pulsations, on the basis of another and more variable quantity, the velocity pressure of the meter."

The error due to pulsating flow was based on the velocity, or quantity of flow, or its proportional equivalent the square root of the pressure difference through the meter element for pulsationless flow. For the four types of meters used the velocity head is equal to or proportional to the drop, or pressure difference, through the meter element. From whatever cause the pulsating flow may have been produced it is quite evident that its effect would have to be determined from the reading on the meter manometer.

It appears to us, therefore, that while the pressure pulsation seems to be the greatest factor in the error due to pulsating flow it is the velocity head reading that is observed on the meter. In our opinion it is the velocity-head readings as shown by the meter for both conditions of flow that should be compared. In fact we are at a loss to know of any other way of establishing the per cent of error.

Mr. Spitzglass also calls attention to the fact that for the orifice meter and flange nozzle meter the percentages of error increase approximately as the inverse ratio of the velocity heads. The reason he assigns is that as the velocity through the meter element decreases the effect due to the static pressure pulsations increases; and likewise by the same reasoning the apparent increase in percentage of error, as the walls of the pipe are reached, can be explained. This relation for the orifice and flange-nozzle meters can be noted in the following table but it is felt that the data is not sufficient in relation to the behavior of pressure pulsation at different points of the line to warrant more than a mention of this apparent relation.

Owing to the limited capacity of the air compressor it was not possible to experiment with pulsating air flow under varying static pressure conditions. For the dead-end meter connection static pressure changes could be noted and it was observed that a rapid increase in percentage of error occurred with increase of static pressure. Hence in the discussion, where it is stated that a 5-in.

differential would give 145 per cent error for a flow condition of one inch true differential and the same differential of 5 in. would give only 5 per cent error for a true differential of 50 in. of water, it would be unsafe to predict that the differential would still be 5 inches for a 50-in. true differential. A flow under 50-in. head would necessarily require a much higher static pressure which is likely to result in a differential between pulsationless and pulsating flow much greater than the assumed 5 inches and hence the percentage of error would be correspondingly increased.

TABLE 11 FLOW CONDITIONS IN THE TEST LINE

Meter used 1	Static pressure in line above meter, in. water Pulseless 2	 Pulsating 3	 Difference 4	Velocity head by meter man., in. water 5	Maximum error, Per cent 6
Venturi	10			9.29	
		13.5	3.5	30.15	81.0
Orifice	27.7			22.00	
33%		32.0	4.3	26.35	9.5
Orifice	11.8			4.10	
50%		13.4	1.6	10.48	60.0
Orifice	9.8			0.94	
70%		11.4	1.6	4.83	128.0
Orifice	9.4			0.41	
80%		10.8	1.4	2.93	167.0
Orifice	8.9			0.0865	
90%		9.6	0.7	1.083	254.0
Flange-nozzle	13.0			5.59	
1⅓ in.		16.3	3.3	11.73	45.0
Flange-nozzle	10.0			1.64	
1½ in.		11.4	1.4	6.16	94.0
Flange-nozzle	9.3			0.47	
2 in.		9.9	0.6	2.74	143.0
Flange-nozzle	8.7			0.121	
2½ in.		9.4	0.7	1.090	200.0
Pitot	8.8			0.163	
No. 1		9.2	0.4	1.110	162.0
Pitot	8.8			0.224	
No. 2		9.6	0.8	1.000	115.0

The authors are glad to comply with Mr. Spitzglass' request to include a table giving in summary a statement of the flow conditions in the test line:

Columns 2 and 3 give the static pressure in the line for pulseless and pulsating flow respectively. Column 4 gives the difference in static pressure for pulsating flow over pulseless flow for a velocity of flow in the three-inch line of twenty-two feet per second.

It will be noticed that although the flow conditions were uniform for the different meter elements the pulsating effect on the static manometer varied, ranging from 0.4 to 4.3 in. of water. This variation depended upon the kind of meter element used. Those elements which obstructed the pipe most, namely: the venturi, the 33-per cent orifice and the 1⅛-in. flange-nozzle, showed the greatest effect due to the static pulsation. Where the pipe was least obstructed as with the orifice, flange-nozzle, and pitot meters the static manometer showed the least effect. Also the maximum percentage of error is seen to vary approximately inversely as the error shown by the static manometer.

As pointed out in the paper and as further emphasized by Mr. Pigott, the authors believe that very little can be done to establish suitable correction factors for meters operating under pulsating flow and that the solution of the problem is reached when some suitable means is provided which will reduce the pulsations to a negligible point. The adaptation of the "muffler" device is apparently the most effective mechanical device for reducing the pulsations. However, further study and experimentation is necessary to establish the proper combination of throttling and volume space for static pressures and pulsating conditions approaching those in general practice.

The authors feel greatly honored in having their paper reviewed by Mr. John L. Hodgson of England.

Mr. Hodgson takes exception to certain conclusions in the paper, in some cases justly so, and in others due apparently to a wrong interpretation of the paper. He points out the importance of having equal spaces in the manometer connections of the meter and in the case of the photo-pulsometer equal spaces above and below the diaphragm. The authors also recognized the importance of this and so far as possible all manometer connections were made of equal length, although this relation could not be maintained while the manometers were in use. Our experiments showed (see Fig. 23) that, when the manometer tubes were throttled, a throttle-plug, with a diameter of 0.02 in. was necessary to reduce the error from 80 to 60 per cent for the venturi meter, with throttling plug coefficients the same for flow in either direction and other conditions of flow remaining constant. The use of volumes in the manometer connections in various combinations and with uniform and similar connecting tubes, $\frac{1}{8}$ in. diameter opening (see "M," Fig. 4), gave no more favorable results than did the throttle plugs.

With the photo-pulsometer the space below the diaphragm was made equal to the space above as were also the connections to the searching tubes as shown in the corrected drawing of Fig. 11. A partition with a glass shutter extended across the diaphragm chamber so that the diaphragm was equidistant from each wall. The diagrams showing negative pressure could not therefore be caused by unequal capacities. The photo-pulsometer was used chiefly as an indicator for illustrating and confirming pulsationless flow conditions.

It is conceivable that the pressure pulsations might be lessened, perhaps nearly eliminated, by the use of the proper amount of throttling, observing at the same time that equal spaces were provided at the manometer connections for varying quantities of flow. We concluded that it was an extremely doubtful and uncertain method, if not wholly dangerous, to rely too fully on such expedients for reducing the pulsating error.

The question raised in regard to the relative effect of the pulsation on the static pressure is answered, we believe, in the reply to Mr. Packard. The authors have designated as static pulsation changes all pulsating changes which act in a direction at right angles to the stream flow. For the venturi meter, with the usual static pressure connections, acting under pulsating flow, the liquid in the manometer tubes would steadily rise until a differential head was reached equal to more than three times the differential head due to pulsationless flow. The column would vibrate through a range of $\frac{1}{2}$ to $\frac{3}{4}$ of an inch corresponding in frequency to that of the flowing air. This vibration is due, in our opinion, to the in and out flow through the manometer tubes, and represents the only effect on the manometer tubes due to the velocity pulsation, the greater part of the manometer reading being due to the static pulsations.

We agree with Mr. Hodgson and Mr. Packard that the velocity of propagation of the pulsating wave approaches that of sound in the flowing fluid plus the velocity of the flowing air. However, in our opinion, as based on our experiments, we are not willing to concede that the pressure pulsation has a less effect than the velocity pulsation in meter installations where these pulsations act on manometers with static connections at right angles and even with the inside of the pipe. From the "dead-end" flow experiments it would also seem evident that the pressure pulsation effect is many times greater than that due to the velocity pulsation.

The statement was made by Mr. Hodgson that the simplest way of reducing the pulsation by the use of a capacity combined with throttling was not mentioned by the authors. In conclusion *B* (*s*) we have stated that the "muffler" device, a combination of capacity, or volume, with throttling is probably "the most effective device for the mechanical elimination of pulsations." The capacity or "muffler" was always inserted between the disturbing element and the meter. It would not seem advisable in our opinion, to insert the throttling device in the line below the meter. It would seem better to eliminate the pulsations as far as possible before the meter was reached.

The authors regret that Mr. Hodgson's paper containing his latest investigations involving the development of a formula for pulsating flow was not available for examination and study until after their paper was written. The grouping of the factors involved in pulsating flow in order shown in the formula seems feasible. Mr. Hodgson is to be congratulated in being able to reduce the results of his researches to a working formula which shows the factors involved in their proper relation. We are in full accord with the opinion of Mr. Hodgson that the only sure way to meter pulsating flow is to reduce the pulsations by means of suitable capacity and throttling, and we likewise believe that even the formula proposed, or any similar formula, while serving in a general way cannot be too rigidly applied in practice. Each installation will present its own peculiar problem.