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JOLIET REFERENCE GAS METER

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ABSTRACT

Upon invitation, the National Bureau of Standards, cooperated with the Peoples Gas Light and Coke Co., Chicago, Ill., in the design, construction, and testing of a reference gas meter capable of being used over a wide range of conditions and having a high maximum capacity. The meter is of the proportional type in which the main gas stream is divided into a large and a small stream in a known or determinable ratio. The rates of flow in the two streams may be varied and the actual ratio of the mass rates of flow is determined by a thermal method. Two heat exchangers, one in each gas stream, receive heat through the medium of hot water from a common source. The rates of flow of the hot water to the two heat exchangers are adjusted until the temperatures of the outlet water streams are the same. The outlet water streams are discharged into weighing tanks from which the ratio between their rates of flow is obtained.

The rates of flow of the gas in the two streams are then adjusted to bring together their temperatures on the outlet side of the heat exchangers. Hence, if the two gas streams are warmed through one temperature range, while the two water streams are cooled through another temperature range, the ratio of the mass rates of flow of the gas streams will be equal to the ratio of the mass rates of flow of the water streams.

The rate of flow in the small gas stream is measured with a large piston meter. The pressure and temperature of the gas in the piston meter are carefully measured, and the specific gravity of the gas, referred to air, is determined. With these data, and the displacement of the piston for the duration of the test, the density and total mass of gas that passed through the small passage are computed. Dividing this total mass flow by the duration of the test gives the mass rate of flow through the small branch.

The total mass rate of flow into the reference meter may now be computed by the formula

$$w=w_S(C_m+1)$$

in which

w(lb/sec) = total mass rate of flow into reference meter.

w_S(lb/sec) = mass rate of flow through the small stream.

C_m = ratio of mass rate of flow in the large stream to that in the small stream,

= ratio of mass rates of flow of water into the two heat exchangers.

The operation of the piston meter is described, and the procedure of making a test with the reference meter is outlined.

The results of 15 tests of an orifice meter with the reference meter are presented and discussed. It is shown that excepting for the determination of the specific gravity of the gas, which is done with auxiliary equipment apart from the meter, the probable uncertainty in any item or factor will not affect the indicated rate of flow by more than about ±0.05 percent.

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I. INTRODUCTION

Disputes have sometimes arisen over the correctness of registration of large-capacity gas meters, and on some of these occasions it would have been advantageous to have a reference meter available with which the meter in question could be compared over the range of its operating conditions. Similar occasions may arise in the future.

The reference meter to be used in such cases should have, among others, the following characteristics:

1. *Accuracy.*—The probable errors of indication should be low, certainly not over 0.5 percent and preferably not over 0.1 or 0.2 percent.

2. *Range.*—It should be possible to operate the meter under a wide range of conditions as regards mass rate of flow, pressure, temperature, and composition of the gas.

3. *Pulsations.*—The meter should be free from the effects of pulsations in the gas stream.

A meter which, it is believed, meets these requirements for a reference meter, has been constructed and installed at the Joliet Meter Station of the Chicago District Pipeline Co., near Joliet, Ill. For this reason the meter will be referred to here as the Joliet reference meter. It is connected in series with and on the downstream side of a 10-in. orifice check meter. This check meter can be connected in series with any one of 12 regular 10-in. orifice-meter runs. Six of these twelve runs are owned by the Chicago District Pipeline Co. and the other six by the Natural Gas Pipeline Co. of America. The discharge from the reference meter is connected into the outlet line from the station. These connections to the reference meter can readily be altered to permit connecting other meters in series with it.

The design and construction of the reference meter presented many problems. The solution of these problems and the final construction of the meter were made possible by the interest and support of the Peoples Gas Light and Coke Co., Chicago, Ill.

One of the functions of the National Bureau of Standards is to develop improvements in making measurements for both laboratory and commercial purposes and to cooperate with others in similar undertakings. Therefore, when invited to cooperate in designing and constructing a reference meter which, it was hoped, would fulfill the above requirements the Bureau accepted. Its cooperation consisted in furnishing information and advice on some of the materials used and the design and testing of some of the meter parts, and in the loan of scientific laboratory instruments.

The essential features of design and operation of the reference meter were evolved [1] by one of the authors (Benesh), who also made the necessary arrangements incident to its construction. Another of the authors (Witting) designed many of the separate parts of the meter and supervised the assembling and testing of the meter. The remaining author (Bean) acted in a liaison capacity between his colleagues and the Bureau, and assisted in some of the tests of the meter and in the writing of this paper.

II. GENERAL PRINCIPLE OF OPERATION

The Joliet reference meter is essentially a large proportional meter. In conformance with the principle of this type of meter, the main gas stream is divided, upon entering the meter, into a large and a small stream. The rates of flow of gas in these two streams are controlled by adjustable restrictions in the outlet passages of the two streams. The ratio of the mass rate of flow in the smaller stream to that in the larger stream is determined by the following thermal method. Heat exchangers, located in the two gas stream passages, receive heat through the medium of hot water from a common source. By means of valves the ratio of the rates of flow of water through the two heat exchangers is adjusted until the water streams leaving the heat exchangers are at the same temperature. The rates of flow of water from the two heat exchangers are determined by weighing the discharge from each. In a somewhat similar manner the rates of flow of gas are so adjusted that the two streams issue from the heat exchangers at the same temperature. Thus, if the two gas streams are heated through the same temperature range, ΔT_g, while cooling the two water streams through a common temperature range, ΔT_w, the ratio between the mass rates of flow in the two gas streams will equal the ratio between the mass rates of flow in the two water streams, which latter has been determined by weighing.

Upon leaving the heat exchangers the smaller gas stream is directed through a piston meter. The temperature and pressure of the gas in the piston meter are carefully controlled and measured. These quantities, together with the displacement, or volume indications of the piston meter, enable one to compute the mass rate of flow of gas in the small stream (assuming of course that the necessary physical properties of the gas are known).

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[1] United States patent 2015249 covering these features has been dedicated to the public.

The mass rate of flow of gas, w, entering the reference meter may be computed by the equation

$$w(\text{lb/sec}) = w_S(C_m + 1), \tag{1}$$

in which

$$C_m = \text{the proportioning ratio,}$$

$$= \frac{\text{mass rate of flow in large stream}}{\text{mass rate of flow in small stream}}.$$

$$w_S(\text{lb/sec}) = \text{mass rate of flow in small stream.}$$

III. SOME GENERAL CHARACTERISTICS OF THE JOLIET REFERENCE METER

The Joliet reference meter was designed and constructed to operate under gas pressures ranging from atmospheric to 600 lb/in^2. It can readily be operated with incoming gas temperatures ranging approximately from −20 to +180° F. To operate at pressures or temperatures very much outside these limits would not change any of the basic principles of operation but would require many changes in the details of construction.

The meter is not affected by any pulsations there may be in the gas stream, provided there is no actual reversal in the direction of flow. Moreover, the meter will not introduce any pulsations. It will operate satisfactorily with any gas or vapor, but will not operate correctly if the fluid to be metered is a mixture of a liquid and vapor, i. e., a fog. In this case, either the liquid should be separated and the two fluids measured separately or the fluid mixture should be heated until it is all vapor, and then metered.

The proportioning ratio can conveniently be varied from about 5:1 to about 60:1. These proportioning limits are not imposed by the construction of the meter but are believed to be the limits of convenient operation. The temperature ranges through which both the water and gas are changed may be varied over rather wide limits. Thus, for any given rate of flow of the gas, the meter may be operated with various proportioning ratios and temperature ranges—a characteristic which may be utilized in checking the indications of the meter and in analyzing the possible sources of error.

As will be more fully discussed later, both the maximum and minimum capacities of the meter depend, in part, upon the relative heat-transferring capacities of the heat exchangers. The maximum capacity depends also upon the strength of some of the parts. As constructed, the meter has a maximum capacity of about 120,000 ft^3/hr of natural gas at 200 lb/in.^{2}, which is equivalent to about 1,633,000 ft^3/hr when the pressure is reduced to atmospheric. The minimum capacity as a proportional meter is about 2,400 ft.^{3}/hr at 200 lb/in^2. Very much lower rates of flow may be metered by blanking off the outlet of the large gas stream so as to divert all the gas through the piston meter.

IV. DETAILED DESCRIPTION OF THE JOLIET REFERENCE METER

1. CONDITIONS TO BE FULFILLED

In order to make use of the assumption that the ratio of the mass rates of flow of gas in the two gas streams is equal to the ratio of the weights of water discharged from the two heat exchangers in a given interval of time, it is necessary that the following requirements should be fulfilled:

1. The temperature of the gas entering the small heat exchanger must be the same as that of the gas stream entering the large heat exchanger.
2. There should be no transfer of heat from one heat exchanger to the other or from one gas stream to the other; neither should there be any cross transfer of heat from either heat exchanger to the other gas stream.
3. There should be no transfer of heat between either the heat exchangers or the gas streams and the outside.
4. The temperature of the water entering the small heat exchanger must be the same as that of the water entering the large exchanger.
5. There should be no transfer of heat between the water connections of one heat exchanger and the gas stream passing over the other heat exchanger.
6. The temperature of the water leaving the large heat exchanger must be equal to that of the water leaving the small heat exchanger.
7. The temperature of the gas leaving the large heat exchanger must be equal to that of the gas leaving the small heat exchanger.

In endeavoring to fulfill these requirements particular attention was given to methods of heat insulation and temperature measurement. While provisions for fulfilling all of them are embodied in the construction of the meter, the final fulfillment of requirements 6 and 7 is a part of the procedure of operating the meter.

2. GENERAL ARRANGEMENT OF PARTS

The general arrangement of the meter is shown diagrammatically in figure 1. The gas enters the proportioning chamber at the left and flows through mixing baffles A. The division of the gas takes place at the upstream face of inlet radiation shield B, the small stream entering the central tube and the large stream flowing along the annular space outside it.

The heat exchangers, indicated by C, are located a few inches from the inlet radiation shield. After passing through the heat exchanger the large gas stream flows through the second series of mixing baffles A′, through the two outlet radiation shields B′, and out of the proportioning chamber.

The small gas stream is conducted from the proportioning chamber to relief bell chamber R of the piston meter. A slide valve, located in the base of R (but not shown in fig. 1) directs the gas to displacement piston chamber P, and back to the top of the relief bell chamber, whence it passes through adjusting valve K, and joins the large gas stream.

The other parts of the meter shown in figure 1 are as follows: D is the boiler, which is the primary source of heat supply. E is a steam-fed water heater where the water for the heat exchangers is heated. F is a valve for regulating the temperature of the water to the heat exchangers. G and H are, respectively, the large and small weighing tanks for determining the amounts of water discharged from the two heat exchangers. I is the storage tank from which the water is circulated to the heat exchangers and back by means of motor-driven pump J.

L is a large-area orifice placed in the outlet pipe of the large gas stream to provide a pressure drop slightly in excess of that occurring in the small gas stream due to friction in the passages of the piston meter. The size of this orifice may be changed and by this means the proportioning ratio may be varied over a wider range than would be possible with valve K alone. M is a large regulating valve by which the main rate of flow through the reference meter is controlled.

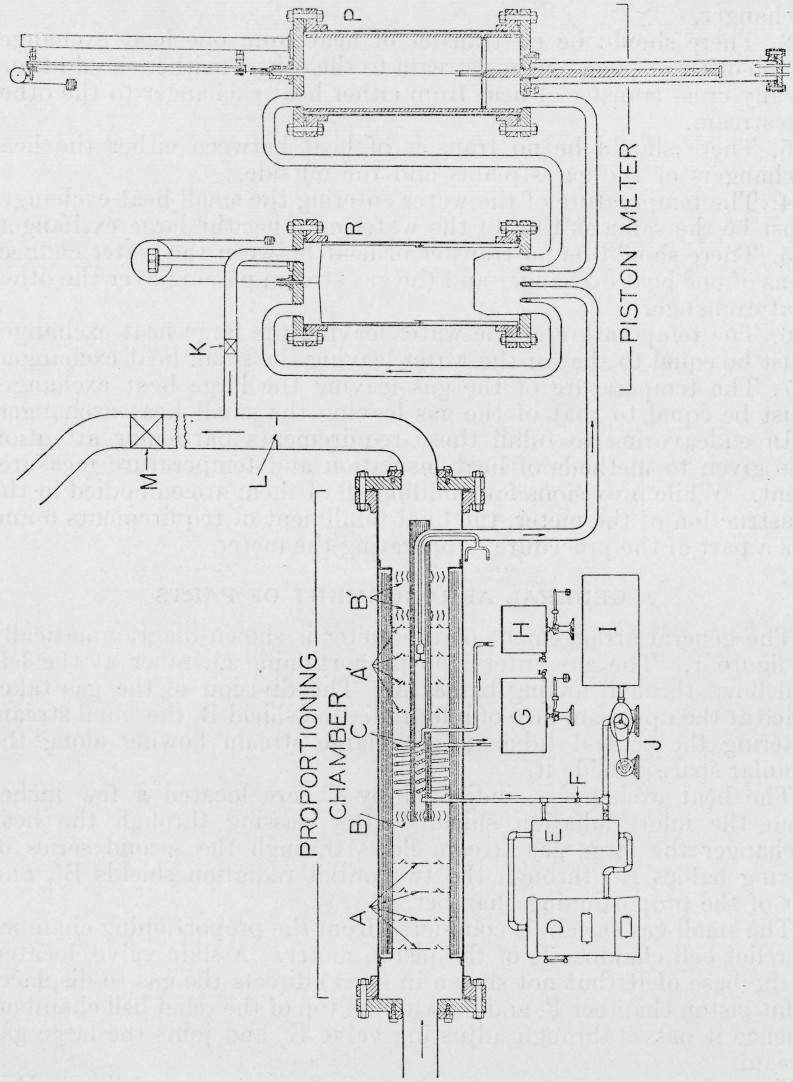

FIGURE 1.—*Schematic diagram of arrangement of the reference meter parts.*

3. PROPORTIONING CHAMBER

Figure 2 shows a horizontal section through the proportioning chamber. The chamber is 12 ft. long, and the outer wall is a section

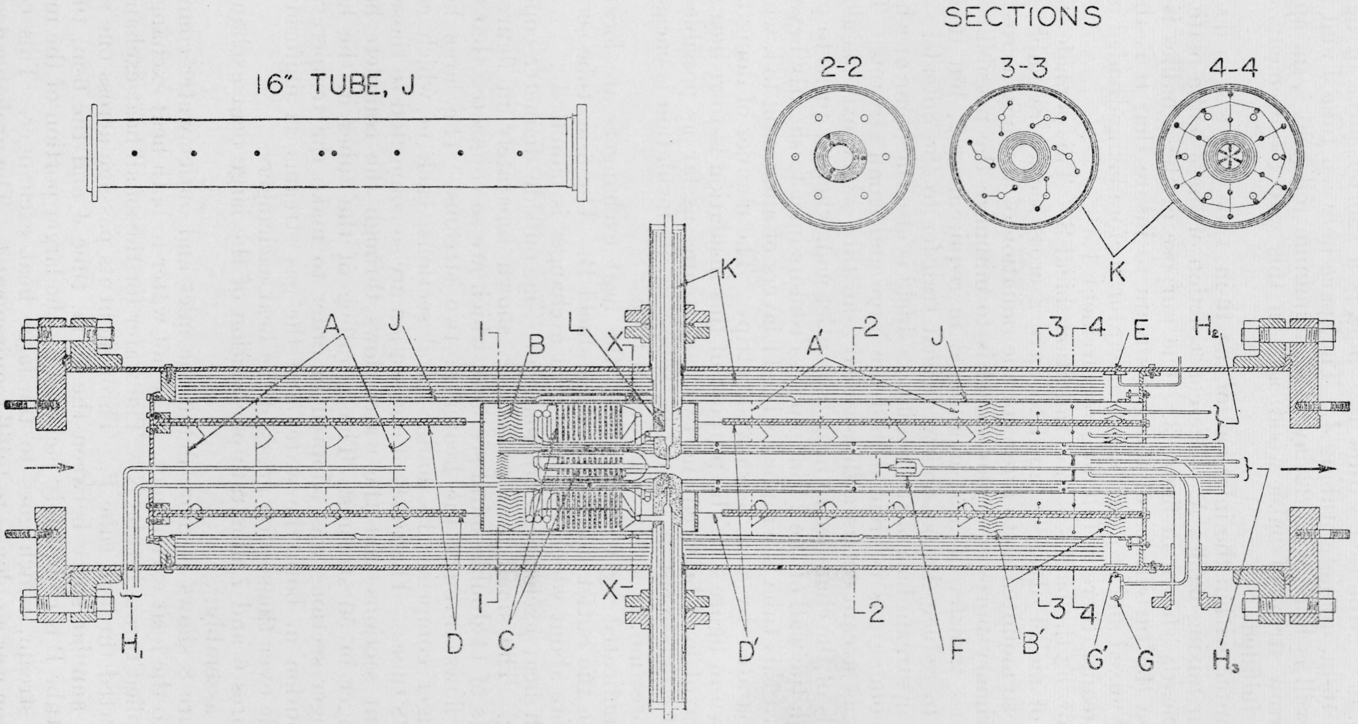

FIGURE 2.—*Horizontal section through proportioning chamber.*

of heavy walled, 24-in. pipe capable of withstanding a gas pressure of 600 lb./in.^{2} Mounted within this pipe is a shorter piece of light-walled 16-in. diameter tubing J. The space between tube J and the outer wall is filled with 22 layers of aluminum foil held ⅛ in. apart by narrow strips of balsa wood, and in this way requirement 3 is partly fulfilled.

Mounted within the inlet end of the 16-in. tube (left end in fig. 2) are four mixing baffles A. The construction of these baffle plates is more clearly shown in figure 3. The purpose of these baffles is to increase the turbulence of the gas stream to insure that it is thoroughly mixed and at a uniform temperature before being divided into two streams, thereby fulfilling requirement 1.

Following the baffles is inlet radiation shield B. This is made from strips of nickel silver stamped to have a cross section resembling a V, and so mounted as to intercept the radiation of any heat across it. The primary purpose of this shield is to minimize the possibility of the cross transfer of heat mentioned in requirement 2, but it also serves to reduce the possibility of heat transfer to the outside.

The upstream face of this radiation shield is also the plane at which the incoming gas is divided into the large and small streams. The small gas stream enters a thin-walled 3-in. tube which extends along the axis of the chamber to near the outlet end, where it turns to pass through the wall of the 24-in. pipe. From its inlet to slightly beyond the turn this tube is wrapped with 11 layers of aluminum foil, which are separated by ⅛-in. balsa-wood strips. The manner of doing this is shown in figure 4. The purpose of this insulation is to reduce the transfer of heat between the two gas streams as far as possible—a part of requirement 2. The 3-in. tube with its insulation is encased, for protection, in a 6-in. thin-walled tube.

As indicated by C in figure 2, the heat exchangers are located close to the outlet side of radiation shield B. The 6-in. tube serves as a core about which the large heat exchanger is mounted.

Both heat exchangers are made of ⅛-in. outside diameter copper tubing. The small heat exchanger, shown separately in figure 5, consists of 11 double-spiral sections, which are so connected that the water flows through the heater in two streams. The large heat exchanger comprises 13 double-spiral sections, each of which contains 28 tubes. The tubes of one section are so connected to those of adjacent sections that the water flows through the complete heat exchanger in 56 streams. The spiralling of the tubes in the heat exchanger sections was adopted in order to make the temperature distribution in both the water and the gas streams as uniform as possible over the section areas of the heat exchangers.

Figures 6 and 7 illustrate one section of the large heat exchanger before assembly.

Figure 8 shows in more detail the inlet and outlet water connections to the heat exchangers. The hot water to both heat exchangers is supplied through tube N. The water for the small heat exchanger is diverted through tube P. Throughout its passage across one side of the annular space between the 16-in. tube J and the 6-in. tube, small tube P is completely jacketed by the larger portion of the main water stream, which goes to the large heat exchanger. This construction was employed to fulfill requirement 4. The probable degree

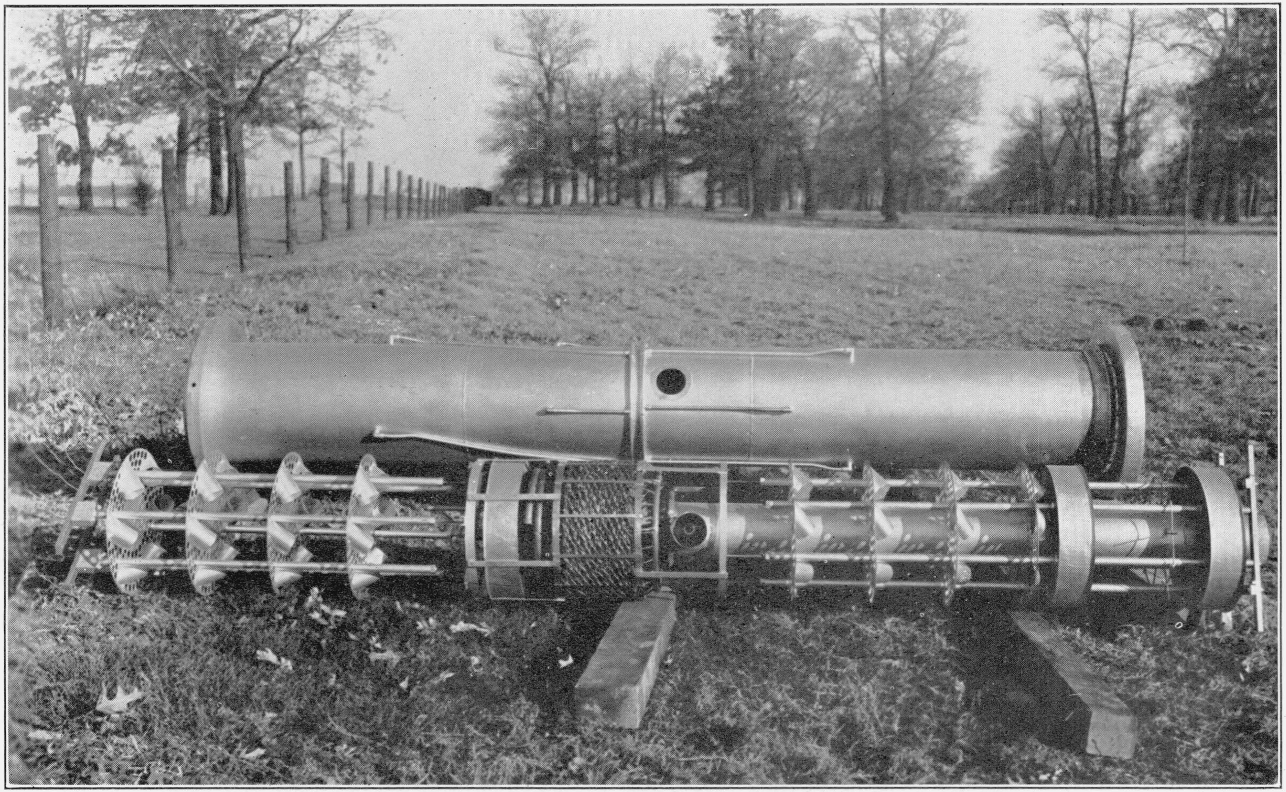

FIGURE 3.—*Baffles, radiation shields, and heat exchanger assembly (foreground) before being placed in 16-inch tube (rear).*

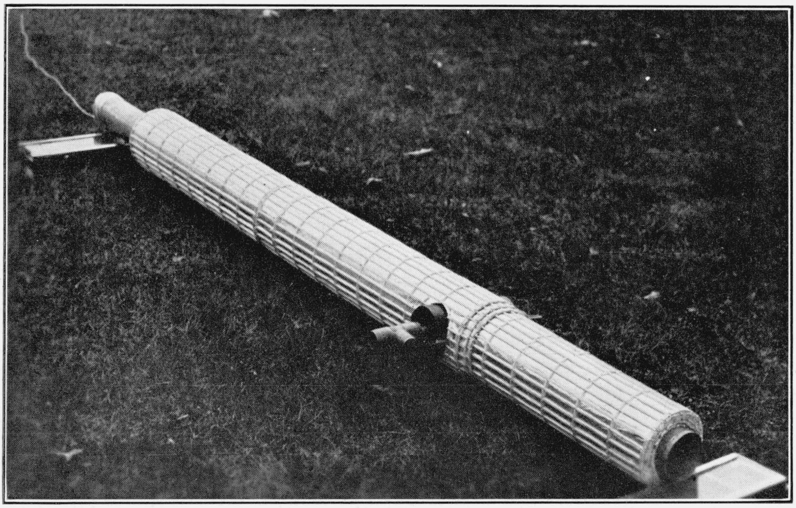

Figure 4.—*Application of aluminum-foil insulation to small gas stream passage.*

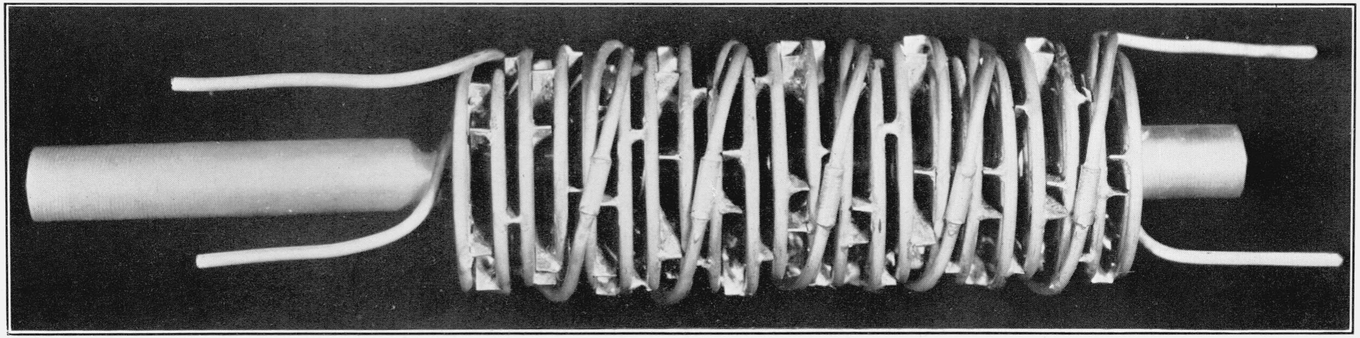

FIGURE 5.—*Small heat exchanger before being placed in the proportioning chamber.*

The upstream (left) end of the core, which is a thin-walled tube, is capped so that no gas flows through it.

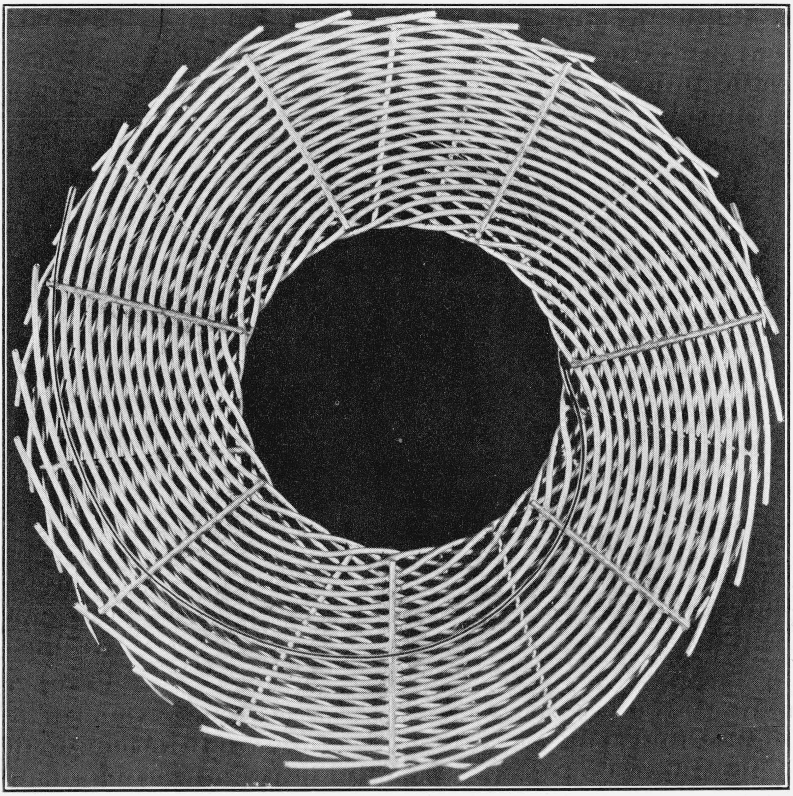

Figure 6.—*Section of the large heat exchanger.*

One tube has been marked to facilitate tracing the path.

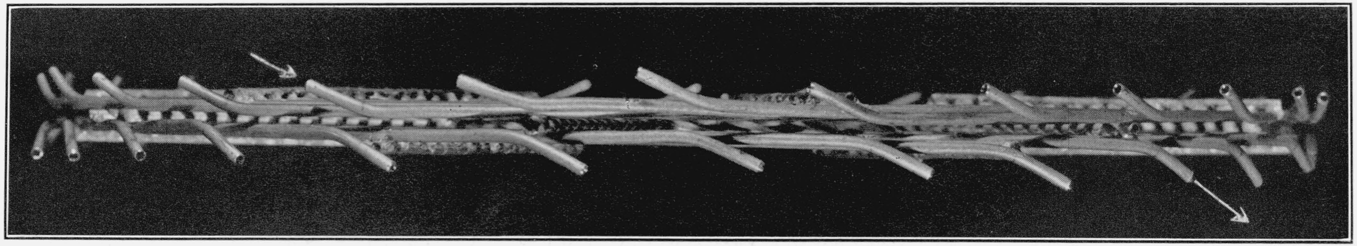

FIGURE 7.—*Section of large heat exchanger.*

Side view. Arrows indicate the ends of one tube.

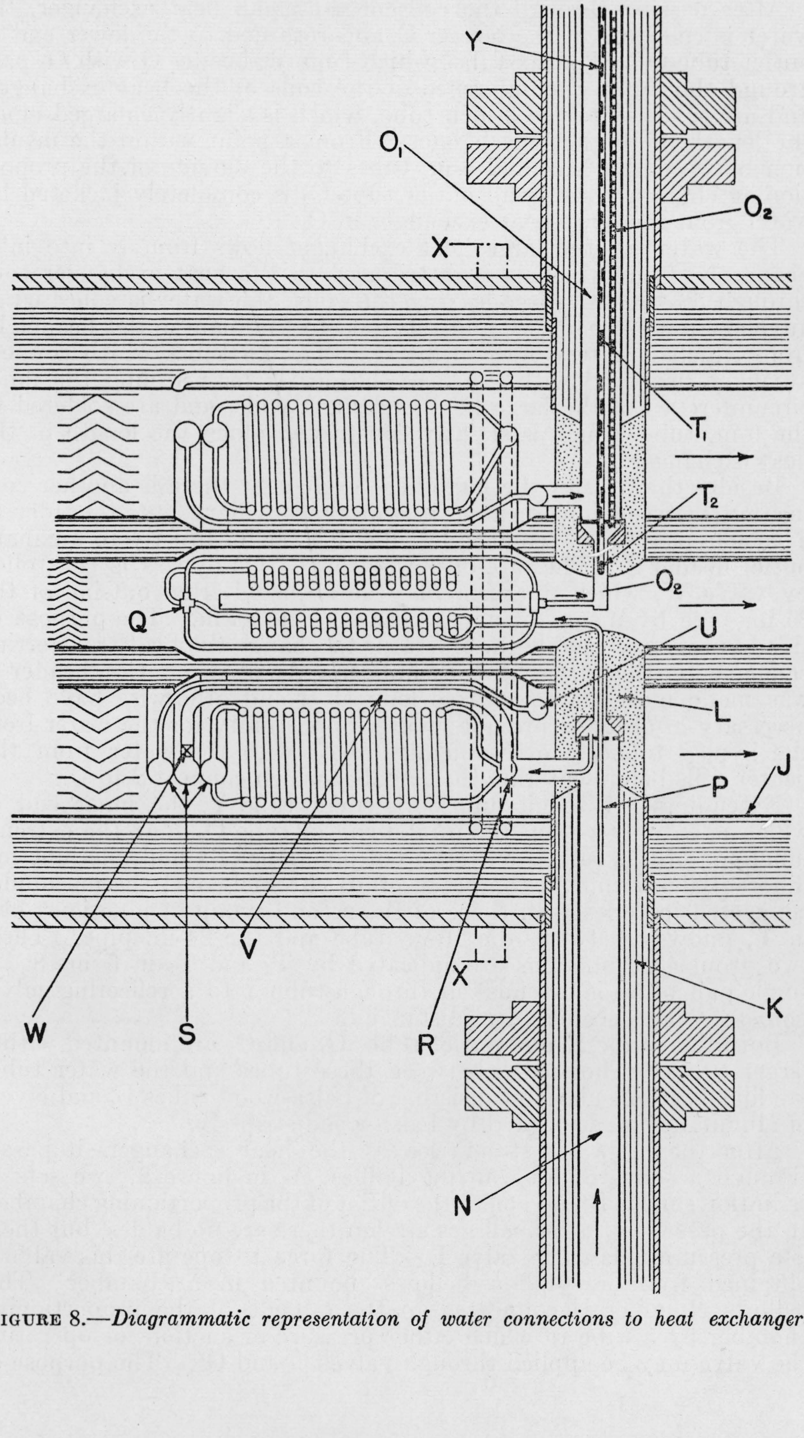

FIGURE 8.—*Diagrammatic representation of water connections to heat exchangers.*

to which the methods of insulation used reduce heat losses is discussed in a later section.

After passing through the coils of the small heat exchanger, the water is collected in the header Q and returned to the lower end of outlet tube O_2. The six tubes which connect header Q with O_2 pass around the outer circumference of the coils of the heat exchanger, and are soldered to the 3-inch tube, which is slightly enlarged along the length of the heat exchanger. From a point within the insulation between the 3-in. and 6-in. tubes to the outside of the proportioning chamber, the small outlet tube O_2 is completely jacketed by water from the large heat exchanger in O_1.

The water for the large heat exchanger flows from N into inlet header R, from which it is distributed to the heat exchanger coils through 56 tubes. After leaving the coils, the water is collected in auxiliary outlet header S, and returned to the main outlet header U, from which it enters outlet tube O_1. The 28 tubes which connect auxiliary header S with the main header U pass around the inner circumference of the large heat exchanger coils, and are soldered to the 6-in. tube, which is slightly constricted along the length of the heat exchanger.

Besides the coils of the large heat exchanger there is another connection between inlet header R and the auxiliary outlet header S. This is bypass tube V connecting inlet header R, directly to auxiliary outlet header S. The rate of flow through this bypass is controlled by valve W, which, in turn, may be adjusted from outside of the 24-in. pipe by means of an extension to its stem. The purpose of this bypass is to enable the operator to change the heat transferring capacity of the large heat exchanger. Auxiliary outlet header S was made more than twice as long as would otherwise have been necessary in order to provide greater opportunity for the water from the bypass to become thoroughly mixed with the water from the heater coils before entering the 28 tubes which connect S to U.

Extending in through tube O_1 is small tube Y, the inner end of which is entirely within the intake end of tube O_2. At the extreme inner end of this tube is one group of junctions of a multiple-junction differential thermopile composed of 18 chromel-copel thermocouples connected in series with those of the second group of junctions, also in Y, midway between the 16-in. tube and the 24-in. pipe. These two groups of junctions are indicated by T_2 and T_1 in figure 8. A single pair of leads extends out through tube Y to a reflecting galvanometer with a scale at 1 m distance.

Both inlet tube N and outlet tubes O_1 and O_2 are mounted within larger tubes. The spaces between these tubes and the water tubes are filled with insulation consisting of balsa-wood cubes L, and layers of aluminum foil separated by balsa-wood strips K.

After the large gas stream leaves the heat exchangers it passes through a series of four mixing baffles, A′ in figure 2, two sets of radiation shields B′, and on to the outlet of the proportioning chamber. In the passage of the small gas stream there are no baffles, but there is a pressure balancing valve F. The force to operate this valve is obtained from a sylphon bellows mounted in a chamber. This bellows chamber is connected to the outside of the proportioning chamber by a tube to which either pressure or suction for operating the valve may be applied through valves G and G′. The purpose of valve F is to introduce additional pressure drop in the small gas stream so that the pressure drops in the two gas streams will be more nearly the same, since without it, the pressure drop in the large gas stream would be greater at most rates of flow, than in the small stream. The difference of pressure between the two streams is measured by a mercury manometer connected to pressure tubes H_2 and H_3.

Located across sections 2–2 and 3–3, figure 2, between radiation shields B′, are two sets of thermocouple junctions. At section 2–2 there are 12 single junctions, and the leads from each junction go to a junction block on the outside of the proportioning chamber housing. By means of this junction block it is possible to connect any one of the 12 junctions in series with any one of the remaining 11 junctions in a galvanometer circuit. In this way it is possible to determine the difference in temperature between any two of the 12 junctions within about 0.02° F.

Distributed over section 3–3 there are in all 36 junctions comprising a second multiple-junction differential thermopile. As shown by the view of section 3–3 in figure 2, 18 of these junctions are spaced uniformly over the cross section of the large gas passage, and the other 18 are distributed over the section of the small gas passage. These two groups of junctions are connected in a circuit containing a second reflecting galvanometer.

At several sections along the chamber single thermocouple junctions have been attached to the inner and outer walls of the small gas stream passage. Section 2–2, figure 2, illustrates such a section. Other junctions have been placed along the surface of the 16-in. tube J. In figure 2 the locations of the thermocouple junctions are indicated by the solid dots. The purpose of the junctions is to make it possible to measure the differences in temperatures between these various points in the proportioning chamber.

At the inlet end of the proportioning chamber, the annular space between the 24-in. pipe and the 16-in. tube is completely closed by a solid supporting ring. At the outlet end this space is normally open so that the entire space is subjected to the outlet pressure. Thus, regardless of the pipe-line pressure, the 16-in. tube will never be subjected to a greater pressure difference than that due to the friction drop along the chamber. In order to be able to test for leaks, provision has been made for completely sealing off this space by means of rubber tube E, figure 2, which may be inflated at any time through a tube to the outside.

As the gas in the large passage flows through the heat exchanger its temperature rises, and ordinarily the temperature of the adjacent section of the 16-in. tube would follow this temperature change to some extent. This would tend to increase the heat loss by radiation and conduction. An attempt has been made to reduce these effects as much as possible by arranging for most of the temperature change between the inlet and outlet ends of the 16-in. tube and 24-in. pipe to take place over a very narrow band, which, for convenience, may be called the band of temperature change. At the section X–X, figures 2 and 8, the 16-in. tube is encircled by two 0.5-in. tubes placed about 1 in. apart. These tubes are clearly shown in figure 3, just to the left of the large hole in the 16-in. tube. Each encircling tube is connected to the 16-in. tube by several pairs of longitudinal tubes, as also shown in figure 3. Consider first the upstream (left in fig. 3) encircling tube and its connecting tube. Because of the baffles and radiation shield within the 16-in. tube, the static pressure of the gas at the openings of the long longitudinal tubes will be slightly higher than at the openings of the short longitudinal tubes. Some gas will therefore enter the longer tubes, flow to and around the encircling tube and back into the large gas stream through the short tubes. This circulation of the inlet gas will tend to keep the 16-in. tube at the inlet gas temperature as far downstream as the encircling tube.

Opposite the two encircling tubes the 24-in. pipe is encircled by two sheet metal disks 2 in. apart, which form a hollow partition between two sets of water sprays. The water sprayed onto the inlet portion of the casing is maintained at the inlet gas temperature, as nearly as possible, while that sprayed onto the outlet section is maintained at the outlet gas temperature.

4. PISTON DISPLACEMENT METER

The tally meter used to measure the small gas stream is a piston meter of the positive displacement type. As is shown in figure 1, this meter has two main parts or chambers, the first being the relief bell and valve chamber R, and the second, measuring chamber P. The side wall of each chamber is a 5-ft length of 24-in. heavy-walled steel pipe. One series 60 and three series 40 blind flanges form the tops and bases of the chambers, the heavier flange serving as the base of the measuring chamber. This heavy construction of these chambers was adopted so that the meter might be safely operated under line pressures as high as 600 lb/in^2.

The measuring cylinder is made of cast iron about 1 in. thick and about 5 ft. long. It was machined on the outside and carefully ground on the inside to an average diameter of 20.522 in. With this cylinder in a vertical position, measurements of four diameters in each of five sections agreed within ± 0.001 in. The sections at which these measurements were made were spaced uniformly along the length of the cylinder. The cylinder stands on a thin paper gasket in a groove cut in the series 60 blind flange. It is entirely free of the chamber walls and top, so that variations in the gas pressure should not affect its volume. The annular space between the cylinder and chamber wall is partly filled with oil so as to prevent gas leaking through the joint between the cylinder and base.

The piston, also of cast iron, has three grooves. The two outside grooves hold cast-iron piston rings, while the middle groove acts as an oil distributing header. Each piston ring is backed with 24 coil springs that give it bearing pressures equal to those used on steam engines. The oil distributing header is connected to a small oil reservoir located on the top of the piston at its center. The level of the oil in this reservoir is kept high enough that the pressure of the oil in the oil groove is greater than that of the gas on either side of the piston. Thus, oil will continually seep out between the piston and cylinder and prevent gas leakage past the piston.

A 2-in. piston rod, fastened to the under side of the piston, extends through a lapped bronze bushing in the cylinder housing base into the oil-power cylinder. As will be more fully explained, oil pressure against the end of this rod operates the piston. In addition, the rod serves as a guide to keep the piston from tilting.

In order to compute the piston displacement, the stroke of the piston must be known. This is measured as follows: A phosphor-bronze wire extends from the top of the piston, through a lapped gland on top of the cylinder housing and is attached to a steel contact button. At the top of a 6-ft post mounted on the cylinder housing there is a pulley over which a steel ribbon passes. One end of the ribbon is attached to the contact button and the other to a counterweight, which keeps the ribbon and wire taut as the piston moves up and down. As the piston nears either end of its stroke, the contact button passes through a guide sleeve and comes to rest against the arm of a dial micrometer or indicator. The piston remains at the end of the stroke long enough for a reading of the micrometer to be made. The micrometers are mounted on the ends of a rod so that they may be turned simultaneously to bring the ends of the contact arms onto the ends of a steel reference bar, and a second reading of the micrometer taken. By comparing the two sets of micrometer readings, which may be made to 0.001 in., with the known length of the steel bar, the stroke of the piston is determined. Two of these steel bars were made and their lengths compared; then one was taken to the National Bureau of Standards to be calibrated and kept for reference, while the other remains in use at Joliet.

The gland through which the bronze wire passes is in the top of a steel forging mounted on top of the cylinder housing. Just below the gland there is a duct through which oil is fed to the center of the forging, so that the oil may flow down the wire into the oil reservoir on top of the piston. Near the base of the forging there are two small glass windows, diametrically opposed, through which the oil level in the piston reservoir may be observed, the top of this reservoir being a glass tube.

Within the relief bell housing there is a sheet-metal inner wall attached at the base to the housing wall and extending up about half the height of the chamber. The annular tank thus formed is about an inch wide. It is filled with mineral seal oil in which the relief bell is suspended, as shown in figure 9. The relief bell is made of sheet zinc 0.01 in. thick, and is guided by six wires so that it cannot touch either wall of the annular tank. A phosphor-bronze wire fastened to the top of the bell extends up through a lapped gland in the top of the bell housing. The upper end of this wire is fastened to a chain which, in turn, wraps around and is fastened to an aluminum pulley of about 1 ft. diameter. The bell is balanced by a weight suspended by a second chain also wrapped around and fastened to the aluminum pulley. The two chains are of such size that as they wind and unwind from opposite sides of the pulley they balance the buoyancy effect of the oil on the bell. The reason for fastening the chains to the pulley, so that any movement of the bell rotates the pulley without slippage, will be explained later.

In the space under the relief bell there are located the D-slide valve which directs the gas flow to and from the measuring cylinder; the small oil cylinder and piston for operating the D-valve, G, figure 11; the 4-way cock H, which controls the movement of this piston; the two 2-way cocks I, which control the direction of oil flow to the main oil cylinder below the measuring cylinder; and an oil sump or reservoir.

The D-valve and seat are made of cast iron and the sliding surfaces ground to fit. Two oil sprays, one above and the other below the valve, and controlled from outside, permit positive lubrication of the sliding surfaces while the meter is in operation. In this way the possibility of gas leakage between these surfaces is minimized.

Although, for convenience of illustration, it is not so represented in figure 11, the 4-way cock is actually located in the bottom of the oil sump, with its core vertical. An extension attached to the core passes through the base of the bell housing so that, by means of a lever attached to the extension, the cock may be operated from the outside. In one position oil from the pump is delivered to one end of small cylinder G, forcing the piston therein to the opposite end. The movement of this piston moves the gas D-valve from one end position to the other by a simple yoke connection. By means of lugs on this yoke the movement of the small piston also closes one of the 2-way cocks I, and opens the other. These lugs are so placed that the D-valve moves about two-thirds of its travel before the 2-way cocks are moved. Turning the 4-way cock through 90° admits oil to the other end of the small cylinder causing the piston to move the D-valve to its other position and to reverse the open and closed relation of the 2-way cocks.

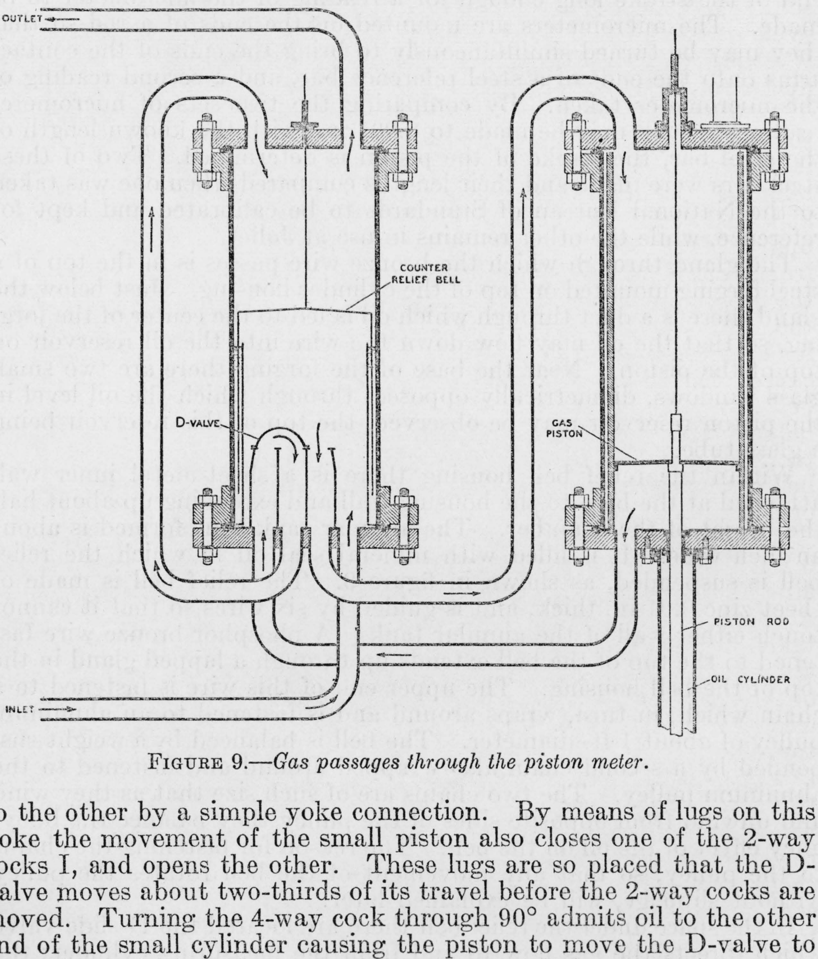

FIGURE 9.—*Gas passages through the piston meter.*

The oil sump is open to the gas pressure and therefore the oil pump supplies only the additional pressure required to operate the large gas piston. This also makes it unnecessary to change the adjustment of the relief valve for different gas pressures.

The outside of the two pressure vessels and all of the gas and oil piping of the piston meter are sprayed with water from a constant-temperature tank. The rate of circulation of the spray water is about 80 gallons per minute. This water may be maintained at any desired temperature by a sensitive thermostat which operates on a temperature differential of about 0.1° F. Both the support for the stroke-measurement mechanism and the calibrated bar are kept at this same temperature by jacketing with water from the constant-temperature tank.

5. HOW THE PISTON METER WORKS

Some of the details of the displacement meter and the functions of some parts already described, can be best explained by describing a cycle of operation. The connections by which the small gas stream is conducted to, through, and from the piston meter are shown diagrammatically in figures 1 and 9.

As the small gas stream leaves the proportioning chamber it passes through a heat exchanger (not shown on any of the sketches) where it is brought to the piston-meter temperature, and it then enters the relief bell chamber on the under side of the bell. With the D-valve at the left end of the stroke, as shown in figure 9, gas will pass from under the bell to the top of the piston. At the same time gas escaping from under the gas piston passes through the D-valve to the top of the bell chamber, whence it is piped back to the main stream. When the gas piston has reached the end of its stroke it remains stationary for a few seconds, during which interval the gas entering the system causes the relief bell to rise, displacing gas from the space above the bell into the outlet connection. Because of the careful counterbalancing and the light construction it requires so little gas pressure to move the bell up or down, that differential pressure across this bell is entirely negligible, regardless of its position, rate of movement, or direction of movement.

As the gas piston nears the end of its stroke (within less than 0.1 in.) the contact button of the stroke measuring mechanism causes an extension attached to the indicator arm to close small snap switch A, figure 10. When the piston has come to rest, the inflow of gas is taken up by the relief bell, which rises and thereby rotates the aluminum wheel. As this wheel rotates, adjustable striker U mounted on the rim closes the second snap switch B. This completes an electrical circuit to supply current from dry-cell batteries to one of the solenoids S. The energized solenoid pulls a trigger that releases a water-filled bucket, which in falling pulls the 4-way cock lever through an arc of 90°. As one water bucket falls, it pulls the other, which is empty, up into place to be filled and ready for the next reversal. Heavy lighting circuit toggle switches T are connected in each solenoid circuit and are operated by the 4-way cock lever in such a way that as soon as the lever has swung a few degrees the toggle switch in the closed circuit is opened, and the other toggle switch is closed. This manner of opening the solenoid circuits protects the small snap switches, which would otherwise be burned out quickly.

As the gas piston moves downward, the piston rod displaces oil from the cylinder, and the oil flows back to the oil sump through the lower 2-way cock, as shown by the solid arrows in figure 11. Near

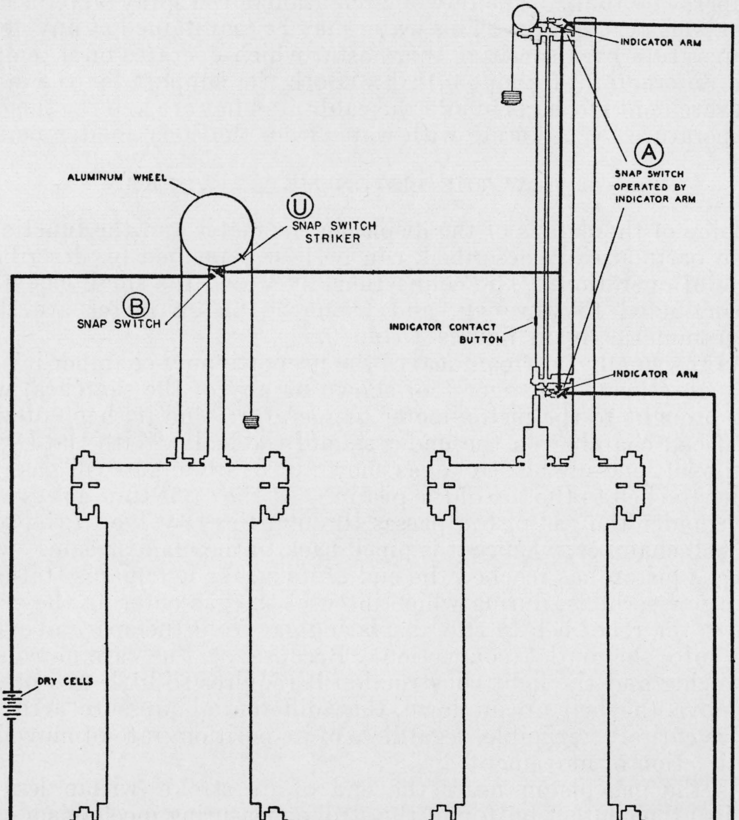

Figure 10.—*Electric circuits which control the operations of the piston meter.*

the end of its stroke the piston rod automatically operates one of two sleeve valves, D in figure 11, which gradually shuts off the oil flow, thus bringing the piston to rest gently. The rate of acceleration or deceleration of the piston may be varied by adjustments of the sleeve valves. The length of time that the gas piston remains stationary at the end of its stroke is regulated by the position of the striker on the rim of the large aluminum pulley.

As previously described, turning the 4-way cock through 90° results in shifting the D-valve and reversing the open and closed positions of the 2-way cocks. With these cocks reversed, oil under pressure from the oil pump starts to flow back into the large oil cylinder and to raise the piston rod and gas piston. As the shifting of the D-valve is completed before the 2-way cocks are fully reversed there is no chance for the gas piston to move before the D-valve is in place.

There are three other valves in the oil line which remain to be described and their functions explained. These are: Valve E, figure 11, for regulating the rate of flow of the oil; valve F for directing the flow of the oil through the proper sleeve valve; and relief valve C.

The connections between valves E and F and sleeve valves D and D′ in the base of the oil cylinder are shown diagrammatically in figure 12. This figure also indicates the essential features of construction of these valves. Starting with the gas piston descending, as in figure 9, oil is leaving the oil cylinder through valves D and F, as indicated by the solid arrows, in Figure 12. When the gas piston has come to rest, the relief bell rises, thereby rotating the large aluminum pulley, figure 11. This pulley is mounted on and rigidly fastened to the core of valve E, and the raising of the bell rotates the core in the direction to open the valve. After the D-valve and the 4- and 2-way cocks have been reversed, as previously explained, oil starts to flow back into the oil cylinder through the same passages, as shown by the solid arrows but in the opposite direction. The inflow of oil into the oil cylinder causes the piston rod and gas piston to rise, thereby releasing valve D, which is opened wide by a spring. With both valves D and E wide open, oil enters the cylinder fast enough to cause the rate of displacement of the gas piston to exceed the rate of inflow of gas under the relief bell, so that the bell falls. As the bell nears the bottom of its travel it nearly closes valve E. This sets up a differential pressure across the valve, which is communicated to the ends of valve F, and as the pressure at end 1 is greater than at end 2, the piston in valve F moves to the right to position 2 shown in dotted outline. This causes the oil to enter the oil cylinder through valve D′, which is also wide open, as indicated by the dotted arrows. The rate of flow of the oil continues to be controlled through valve E by the position of the relief bell, so that the displacement rate of the gas piston exactly equals the volume rate of flow of the gas. It was expected that in order to secure this balance there would be a small amount of "hunting" by the bell, but there has appeared to be almost none.

As the gas piston nears the end of its travel the piston rod engages a link which gradually closes valve D′, bringing the gas piston to rest gently. After the D-valve and 4- and 2-way cocks are reversed oil

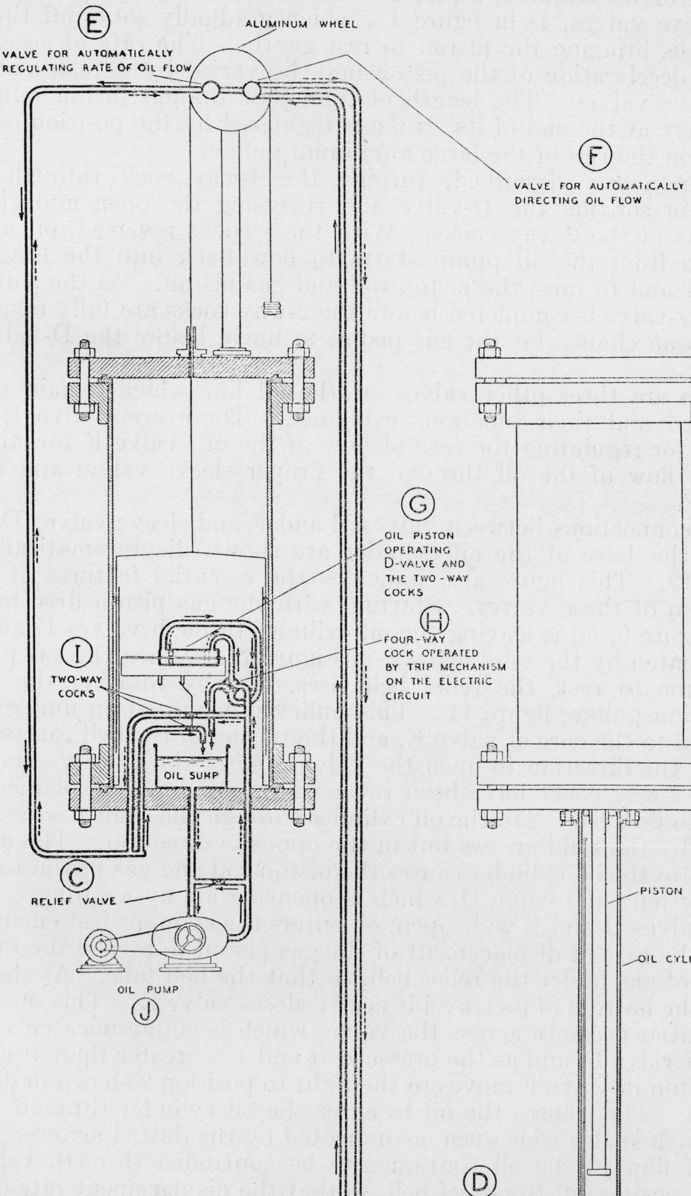

FIGURE 11.—*Diagrammatic representation of the oil circuit by which the power to operate the piston meter is transmitted.*

starts to leave the oil cylinder along the path of the dotted arrows, but in the opposite direction. Again, as the displacement rate of the gas piston overtakes the rate of gas flow the relief bell closes valve E. This time, however, the difference of pressure across valve E is in the

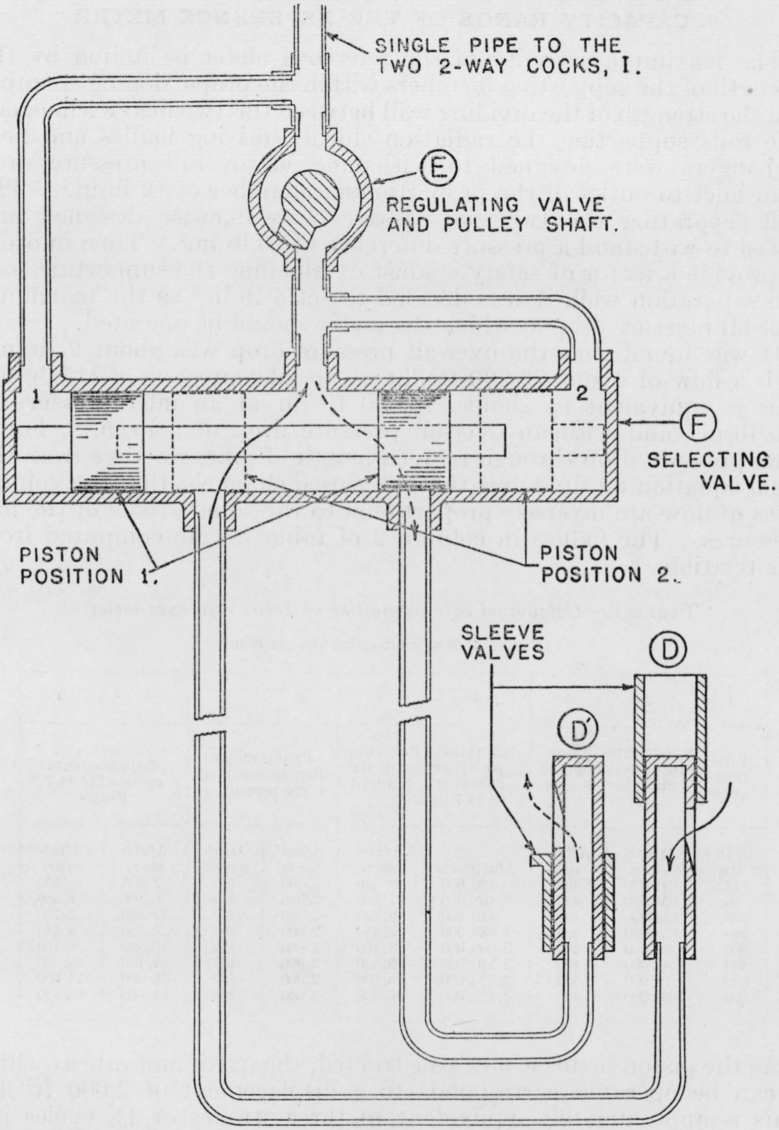

FIGURE 12.—*Diagram of connections between valves* D, D′, E, *and* F.

opposite direction, so that the pressure at end 2 of valve F is greater than at end 1, and the piston in valve F is forced back to position 1. Oil now leaves the oil cylinder along the path of the solid arrows, and a cycle of changes is completed.

Relief valve or unloading valve C, figure 11, is located in a by-pass line connecting the oil-pump discharge to the oil sump. When the gas piston and piston rod are descending and the upper 2-way cock is closed, this relief valve permits the discharge from the pump to return to the oil sump without subjecting the pump and piping to excessive pressures.

6. CAPACITY RANGE OF THE REFERENCE METER

The maximum capacity of the reference meter is limited by the strength of the supporting members within the proportioning chamber and the strength of the dividing wall between the two heat exchangers. The rods supporting the radiation shields, mixing baffles and heat exchangers were designed to withstand an overall pressure drop from inlet to outlet of the proportioning chamber of 10 lb/in.^{2}. The wall separating the two gas passages was likewise designed and tested to withstand a pressure difference of 10 lb/in.^{2}. Then in order to provide a factor of safety against overloading the supporting rods and separation wall, it was decided to set 5 lb/in.^{2} as the maximum over-all pressure drop at which the meter should be operated.

It was found that the over-all pressure drop was about 2 lb/in.^{2}, with a flow of about 73,200 ft^3 /hr at an inlet pressure of 215 lb/in.^{2}. This is equivalent to about 120,000 ft^3 /hr at an inlet pressure of 200 lb/in.^{2} and with an over-all pressure drop of 5 lb/in.^{2}. For a fixed pressure drop through a given length of pipe, we have from the usual equation for fluid flow through closed channels, that the volume rates of flow are inversely proportional to the square roots of the line pressures. The values in column 2 of table 1 were computed from this relation.

TABLE 1.—*Calculated safe capacities of Joliet reference meter*

[All rates of flow are in cubic feet per hour]

1	2	3	4	5	6	7	8	9
Line pressure	Safe rates of flow into proportioning chamber, at line pressure		Safe rates of flow into proportioning chamber, reduced to 14.7 lb/in.^{2}		Piston meter displacements at line pressure		Piston meter displacements reduced to 14.7 lb/in.^{2}	
lb/in.^{2} abs.	*Maximum*	*Minimum*	*Maximum*	*Minimum*	*Maximum*	*Minimum*	*Maximum*	*Minimum*
14.7	120,000	400	120,000	400	2,000	400	2,000	400
50	120,000	400	408,000	1,360	2,000	400	6,800	1,360
100	120,000	400	816,000	2,720	2,000	400	13,600	2,720
200	120,000	400	1,633,000	5,440	2,000	400	27,200	5,440
300	98,000	400	2,000,000	8,160	2,000	400	40,800	8,160
400	84,900	400	2,310,000	10,880	2,000	400	54,400	10,880
500	75,900	400	2,580,000	13,600	2,000	400	68,000	13,600
600	69,200	400	2,823,000	16,320	2,000	400	81,600	16,320

As the piston meter is now constructed, the maximum rate at which it can be operated corresponds to a displacement of 2,000 ft^3 /hr. This is approximately equivalent to three strokes or 1½ cycles per minute. In order to make it operate at a higher rate, it would be necessary to increase the weight of the gas piston in order to provide an increased pressure for driving the oil out of the oil cylinder on the downward stroke; and a higher oil pressure would then be required to raise the gas piston. Moreover, when the piston is moving at a displacement rate of 2,000 ft^3/hr, there is a difference of about 4 in. of water between the gas pressures on the two sides of the piston.

The oil seal, provided by the reservoir and middle piston groove, is adequate to this pressure difference, but it would not be if the pressure difference were increased very much, as would be the case at a higher displacement rate.

Theoretically, the displacement rate of the piston meter may decrease almost to the vanishing point, but practically a minimum rate of displacement is reached when the movement of the gas piston becomes irregular. This irregular operation is apparently due to gas dissolved in the oil escaping from solution and forming gas pockets in the oil piping. In some preliminary trials this difficulty was encountered at a displacement rate of about 400 ft^3/hr or one stroke in 2 minutes. At that time the difficulty was overcome by removing the gas bubbles through vents. There has been no occasion to see how much farther the displacement rate could be decreased in practice, but it is believed that a displacement rate of 100 ft^3/hr or one stroke in 8 minutes might possibly be reached. In preparing table 1 a minimum displacement rate of 400 ft^3/hr is given as a conservative value (column 7), this being the lowest rate at which the meter has actually been operated.

The proportioning ratio at which the meter can be operated depends upon the relative areas of the heat transferring surfaces of the two heat exchangers, and upon the regulation of the water flow, which can be obtained by the by-pass around the large heat exchanger and the valves on the outlets of the two heat exchangers. The range over which this proportioning ratio may be thus varied conveniently is from about 5:1 to about 60:1. Since the maximum displacement rate for the piston meter is 2,000 ft^3/hr this limits the maximum rate of flow into the proportioning chamber to 120,000 ft^3/hr, as shown in column 2, table 1, for line pressures below 200 $lb/in.^2$

If the outlet to the large gas passage is blanked off all of the gas will then pass through the displacement meter. This converts the reference meter from a proportional meter into a simple displacement meter. In this way, also, the minimum capacity of the reference meter becomes the same as the minimum rate of displacement of the piston meter. Hence, in table 1, the figures in column 3 and 5 are the same as those in columns 7 and 9.

V. OPERATING THE JOLIET REFERENCE METER

1. QUANTITIES OBSERVED WHEN OPERATING THE REFERENCE METER

Observations of the following quantities are made and recorded when operating the reference meter:

1. Weight of water from small heat exchanger.
2. Weight of water from large heat exchanger.
3. Gage pressure of the gas in the piston meter.
4. Temperature of the gas in the piston meter.
5. Length of piston strokes.
6. Number of piston strokes or cycles.
7. Duration of run (i. e., length of test period).
8. Specific gravity of the gas.
9. Barometric pressure during the period of the test.
10. Difference between the pressures of the gas in the large and small gas streams at the gas differential thermometer (section 4–4, figure 2).
11. Temperature of the gas entering the proportioning chamber.
12. Temperature of large gas stream at proportioning chamber outlet.

13. Difference in temperatures of water streams leaving the two heat exchangers.
14. Difference in temperatures of the large and small gas streams leaving proportioning chamber.
15. Temperature of the water entering the heat exchangers.
16. Pressures of water at inlet and outlet to heat exchangers.
17. Temperatures of the inlet and outlet sections of the proportioning chamber case (i. e., temperatures of the bath waters with which these sections are sprayed).
18. Temperature of the piston meter bath water.
19. Differential pressure across relief bell.

Items 1 to 9, inclusive, are necessary for computing the rate of flow through the reference meter. Since any error in measuring or recording these quantities will affect the final result in greater or lesser degree, it is necessary to study the effects of errors in each quantity upon the final result, so that each quantity may be measured with the necessary degree of precision.

Items 10, 11, and 12 are not needed in computing the rate of gas flow unless the pressure adjusting valve in the small gas stream F, figure 2, is not used, or is inoperative. In such a case these items are used for computing a small correction for the Joule-Thompson effect.

Items 13 and 14 never enter directly into computation of the flow, but since the determination of the proportioning ratio assumes that these differences are sensibly zero it is necessary that they be indicated and observed very carefully.

The remaining five items are used only as guides in the operation of the meter.

2. INSTRUMENTS AND METHODS OF MEASUREMENT

The weight of the water flowing from the small heat exchanger is determined with an equal arm over-and-under scale. The balance has a capacity of 30 lb, and the value of the smallest weight used with it is 0.1 lb. In addition, the balance is equipped with a scale and pointer with which readings may be made to the nearest 0.001 lb. The general procedure followed when operating the meter is to weigh about 20 lb of water at a time. Two pails of equal capacity are used alternately for collecting and weighing the water.

The weight of water flowing from the large heat exchanger is determined with two beam scales of 300-lb capacity. The beams of these scales have a range of 3 lb divided to ¼ oz. Ordinarily, about 250 pounds of water are weighed at a time and the scale beam setting read to the nearest ounce. Each scale is equipped with a weigh tank, and while one tankful is being weighed and emptied the other tank is filling.

Both of the scales and also the balance were calibrated for commercial accuracy by the Bureau at its track-scale depot in Clearing, near Chicago. In addition, intercomparisons have been made between the indications of these scales and master scales maintained by the Chicago Department of Weights and Measures. The results of these comparisons are utilized in calculating the results of a test.

The gage pressure of the gas in the piston meter, item 3, is measured with a dead-weight gage tester modified as so to be conveniently used as a piston gage. Special weights were made for use with this piston gage, which permitted the measurement of pressures to 0.01 lb./in.^{2}, although it is not always necessary to measure pressures closer than to the nearest 0.1 lb/in.^{2}. During a test, readings of the gas pressure in the piston meter are made at 4-minute intervals. (A more detailed description of this piston gage is given in Appendix B.)

The temperature of the gas in the piston meter, item 4, is not measured directly but is assumed to be the same as that of the constant-temperature bath water. The temperature of the bath water, item 18, is measured with a mercury-in-glass thermometer graduated to 1° F, which has been compared with a thermometer calibrated by the Bureau. The indications of the thermometer in the water bath are estimated to the nearest 0.1° F, and these readings are made at 2-minute intervals.

The length of each piston stroke, item 5, is obtained by readings of the dial micrometers (described in section IV–4) at the end of each stroke. Although it is not necessary to know the stroke of the gas piston to less than 0.01 in., indications of the dial micrometers may be read easily to the nearest 0.001 in.

The number of piston strokes during a test, item 6, is recorded by the observer taking the micrometer readings. Each stroke of the piston is also recorded on a chronograph by means of an electrical connection.

The length of a test period, item 7, is determined by means of a clock with a mercury-compensated seconds pendulum. This clock is equipped with a sweep second hand, and may be regulated so that its variations will be less than 5 seconds a day.

In order to reduce the errors of observing the time at the start and end of a test, and to obtain a permanent record against time of several of the meter functions, a multiple-pen chronograph is used. By means of a photoelectric-cell system, one of the pens records the time in seconds, as measured by the clock pendulum. Other pens are connected to record each stroke of the gas piston, and the starting and stopping of the water flow into each weighing tank.

The specific gravity of the gas, item 8, is determined with a gravity balance. During a test this determination is made at about half-hour intervals.

The barometric pressure, item 9, is determined with a mercurial barometer located in a building about 100 yd from the meter, and at the same elevation. One reading is taken during each test period.

The differential pressures between the gas streams at the section of the differential thermometers, item 10, and across the relief bell, item 19, are obtained with liquid manometers designed to withstand safely the line pressures. Mercury is used in the manometer for item 10, and mineral seal oil in the manometer for item 19. During a test these manometers are read at 2-minute intervals.

The temperature of the gas entering the proportioning chamber, item 11, and the temperature of the large gas stream leaving the proportioning chamber, item 12, are determined with mercurial thermometers similar to that used for item 4. These thermometers are inserted in stainless steel wells partially filled with mercury. The wells are located in the 10-in. pipe conveniently close to the inlet and outlet of the proportioning chamber. Readings of these thermometers are taken at 2-minute intervals.

The multiple-junction thermopiles used to determine the differences in temperatures of the water streams and gas streams leaving the heat exchangers, items 13 and 14, have been described in section IV–3. As there are 18 pairs of chromel-copel junctions in each differential thermometer and the resulting electromotive forces are measured with high quality reflecting galvanometers equipped with scales at 1 meter distance, it is possible to detect temperature differences of about 0.001° F. Item 5 is determined with a mercurial thermometer which is read to the nearest degree Fahrenheit every 2 minutes.

The water pressures at the inlet and outlet to the heat exchangers, item 16, are measured with bourdon-tube type pressure gages, which are read at 2 minute intervals.

The temperature of the water sprayed on the upstream section of the proportioning chamber case, item 17, is obtained with a mercurial thermometer read to the nearest degree Fahrenheit every 2 minutes. The temperature of the downstream section of the case is presumably the same as that of the piston meter because the spray water for both is drawn from a common sump. Each section of the case is sprayed with water at the rate of about 30 gallons per minute.

3. PROCEDURE OF OPERATING THE REFERENCE METER

Before starting a test with the reference meter it is necessary to bring all parts to a state of thermal equilibrium. To do this requires the following operations, which are carried out in close succession or simultaneously by the several members of the crew. All of the pumps supplying water for the sprays are started and the spray-water temperatures brought to the desired values as soon as possible. After these temperatures are obtained, that of the water spraying the inlet section of the proportioning chamber case is maintained by manual control, while that of the water to the outlet section and the piston meter is maintained by a thermostat.

The gas flow through the meter is started and adjusted to the desired rate. The steam boiler is started and also the pump for circulating water through the heat exchangers. The water valves at the outlets of the two main heat exchangers are adjusted to give the desired rate of water flow through each. After steam is up and hot water is being circulated through the heat exchangers, the circuits of the differential thermocouple thermometers in the gas and water streams are closed and the relative rates of flow of the two gas and water streams adjusted until their corresponding temperature differences are approximately zero. Most of this regulation is made by means of the valve in the large heat exchanger by-pass W, figure 8, and the gas valve in the piston-meter outlet K, figure 1. When a stable condition of temperatures has been obtained observation of the differential thermometer galvanometers is discontinued and the circuits are opened to avoid possible injury to the galvanometers, while the reference meter is operated under these adjustments for a period of 1 to 2 hours.

During this stabilizing period the gas flow is kept constant. Since the temperature of the incoming gas is not constant it is necessary continually to adjust the valve in the by-pass of the steam to water heater F, figure 1, so that the temperature of the gas leaving the proportioning chamber shall be approximately equal that of the piston-meter bath water. As the piston of the piston meter is not operated during this period, the relief bell rises out of the sealing oil and permits the gas to flow in and out of the relief chamber without entering the measuring cylinder.

At the end of the stablizing period, oil-pump J, figure 11, is started and the piston of the piston meter thereby set in motion. This automatically causes the relief bell to fall into the sealing oil. The circuits of the differential thermocouple thermometers are again closed, and any necessary adjustments made to the water and gas streams to bring the temperature differences between the two gas streams and between the two water streams substantially to zero. This temperature balance is continually observed and maintained throughout the test, thus fulfilling the conditions 6 and 7, stated in section IV-1.

After the piston meter has been in operation from 15 to 30 minutes, and all conditions about the reference meter have become stabilized, the meter is ready for a test, and the chronograph is started. The start of a test is made when the piston is at one end of its stroke, and the exact instant of starting is when one of the triggers releases the lever of the 4-way cock. The approach of the starting instant is indicated by the aluminum wheel, figure 10, starting to revolve. At the instant the lever starts to move the water streams from the two heat exchangers are diverted into empty weighing tanks. Not only is the shifting of the valves and the diversion of the water streams recorded by the chronograph, but at the instant of starting, the clock is also observed and the time recorded.[2]

Subsequent diversions of the water streams to empty weighing tanks are always made as the valves reverse in exactly the same part of the piston-meter cycle, as indicated by the position of the 4-way cock lever. The procedure for ending a test is similar to that of starting. The most important reason for starting and stopping the test the instant the 4-way cock lever starts to move from one and the same side of its swing is to have the volume of gas under the relief bell at the end of the test equal to that at the start. In order that there might be no lost motion between the movements of the relief bell and the striker on the aluminum wheel the chains supporting the relief bell and its counterweight were fastened to the wheel. In this connection it may be pointed out that it would not be satisfactory to start and stop the run at the instant the large gas piston comes to rest because, due to the deceleration of the gas piston by sleeve valves D, figure 11, the relief bell starts to rise before the gas piston comes to rest.

Throughout a test it is necessary to maintain the total mass rate of flow of the gas as nearly constant as possible. To accomplish this an orifice is located about 30 ft. upstream from the proportioning chamber inlet, and a sensitive differential pressure gage (described in Appendix B) is connected across the orifice. An observer stationed by this gage can keep the differential pressure within very close limits by operating the valve at reference-meter outlet M, figure 1, through a system of pulleys and cable connections. The static pressure in the line is normally maintained constant within a commercial limit of 2 or 3 lb./in.^{2}, by automatic pressure regulators located about 3 miles upstream. If closer regulation than this should be required, an operator could be sent to the regulator station to control the pressure manually.

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[2] This was accomplished by the use of an auxiliary signal to the observer at the clock, since the clock is in a separate building from that housing the reference meter.

VI. TESTS MADE WITH THE REFERENCE METER

1. GENERAL PROCEDURE

To study the performance of the reference meter a series of tests were made of an orifice meter. As already stated, an orifice is used in connection with the regulation of the rate of flow; and the determination of the discharge coefficient of the orifice offered a convenient method of making such a study. For computing the discharge coefficients, the rates of flow calculated from the reference-meter readings were taken as correct. This of course means that any variations found between the values of the discharge coefficient computed from different tests reflect the possible errors of observation and operation of *both* the orifice meter and the reference meter. In making these tests, not only was the rate of flow varied, but the proportioning ratio and the temperature rise of the gas were also varied over such ranges as could be covered conveniently in the time then available.

The data required for the orifice in addition to those for the reference meter were the static and differential pressures at the orifice, and the temperature of the gas passing through the orifice. To obtain more data on the orifice, two pairs of pressure taps were used in connection with the orifice; with one of these pairs, the flange taps, the pressure holes were located 1 in. from the orifice plate; with the other pair, the pipe taps, the taps were 2½ pipe diameters upstream and 8 pipe diameters downstream from the orifice plate.

During these tests a 6-in. square-edged orifice was used in the 10-in. check meter mentioned in the introduction.

The static pressures, taken from the upstream tap in each case, were measured with the same piston gage as used for measuring the static pressure of the piston meter. These pressures were read to the nearest 0.10 lb. every 4 minutes, in rotation with that of the piston meter.

The differential pressures were measured with special piston-type, differential pressure gages. (See Appendix A for detailed description.) These gages were read to the equivalent of 0.002 in. of water once a minute.

The gas temperature was taken to be the same at the orifice as at the inlet to the proportioning chamber, the same thermometer reading being used for both.

2. OBSERVED QUANTITIES AND COMPUTED RESULTS FOR THE JOLIET REFERENCE METER

The observed data from the operation of the reference meter for the 15 tests are presented in table 2. The data in columns 11, 12, and 13, were necessarily obtained from auxiliary apparatus entirely apart from the meter, but are essential to computing the rate of flow through the meter. The data in columns 14 to 19, inclusive, are not needed for computing the rate of flow but are of interest and assistance in operating the meter.

TABLE 2.—*Quantities observed when operating the Joliet reference meter*

1	2	3	4	5	6	7	8	9	10
		Proportioning chamber data					Piston meter data		
Run	Duration of test t	Inlet gas temperature	Outlet gas temperature	Difference gas stream pressures, section4-4 $(p_4)_S-(p_4)_L$	Water through large exchanger M_L	Water through small exchanger M_S	Gas temperature T'	Absolute pressure of gas p	Number of cycles n
	sec.	°F	°F	In Hg	lb	lb	°F	lb/in.^{2}	
1	5,133	62.3	74.8	+0.34	3,048.51	79.453	74.6	220.35	51
2	5,198	64.0	75.2	+.34	2,949.06	77.564	74.3	220.43	52
3	5,572	60.8	73.9	−1.15	2,313.50	156.972	74.2	220.94	138
4	5,604	59.4	74.2	−1.14	2,322.43	158.844	74.1	221.40	140
5	5,610	61.4	67.3	+.39	2,226.62	52.937	67.8	219.03	50
6	5,929	61.9	67.4	+.41	2,171.95	52,756	67.5	217.08	54
7	5,458	60.1	66.8	−1.15	1,590.91	110.234	67.1	219.07	135
8	5,288	58.1	66.7	−1.18	1,601.67	112.730	67.1	220.19	133
9	5,513	60.9	69.0	.0	3,313.13	126.167	69.0	216.28	136
10	4,942	60.5	68.8	+.01	2,828.04	107.554	68.9	215.02	122
11	4,860	61.3	69.9	+1.01	2,867.76	84.218	70.2	215.81	121
12	6,091	57.4	69.0	+1.16	4,246.59	118.044	69.9	214.25	145
13	5,330	56.8	68.8	+1.11	3,530.15	100.670	69.8	212.59	131
14	5,711	59.6	68.3	+1.05	3,522.28	101.941	68.2	212.52	141
15	5,550	57.8	67.9	+1.00	3,476.54	100.514	68.2	213.85	137

	11	12	13	14	15	16	17	18	19
	General			Auxiliary operating data					
					Water pressures, gage			Spray temperatures proportioning chamber	
Run	Barometric pressure p_o	Specific gravity of gas G	Supercompressibility factor of gas y	Water temperature at exchanger inlets	Heat exchanger inlets	Outlet, large exchanger	Outlet, small exchanger	Inlet section	Outlet section and piston meter
	lb/in.^{2}			° F	lb/in.^{2}	lb/in.^{2}	lb/in.^{2}	° F	° F
1	14.43	0.6673	1.0318	136	45	0	16	70.9	74.6
2	14.42	.6697	1.0318	133	41	0	15	71.1	74.3
3	14.39	.6723	1.0318	160	53	25	0	71.0	74.2
4	14.42	.6690	1.0318	179	53	25	0	70.4	74.1
5	14.50	.6687	1.0331	109	48	0	10	61.8	67.8
6	14.50	.6703	1.0327	107	46	0	9	62.3	67.5
7	14.50	.6723	1.0331	129	52	15	0	59.8	67.1
8	14.49	.6747	1.0331	149	52	17	0	60.5	67.1
9	14.44	.6730	1.0318	138	44	0	0	64.2	69.0
10	14.44	.6740	1.0318	141	43	0	0	63.8	68.9
11	14.43	.6723	1.0318	164	42	0	13	64.8	70.2
12	14.29	.6703	1.0316	177	54	0	20	58.1	69.9
13	14.29	.6700	1.0314	186	51	0	17	57.0	69.8
14	14.36	.6740	1.0316	158	45	0	14	64.8	68.2
15	14.29	.6707	1.0314	172	47	0	15	65.0	68.2

Table 3 gives the computed rates of flow of gas through the reference meter, and also the values for the more important intermediate steps.

TABLE 3.—*Computation of rate of flow of gas through Joliet reference meter*

1	2	3	4	5	6	7	8	9	10
								Rate of flow of gas	
Run	Temperature rise of gas in proportioning chamber ΔT_g	Observed ratio of water flows C'_m	Correction factor	Proportioning ratio C_m	Gas density at piston meter conditions ρ_p	Total displacement of piston meter V_p	Mass of gas through piston meter W_s	Through piston meter only w_S	Through reference meter $w_S\ (C_{m+1})$ w
	°F				lb/ft ^{3}	ft ^{3}	lb	lb/sec	lb/sec
1	12.5	38.369	0.99918	38.338	0.76414	1,096.19	837.64	0.16319	6.420
2	11.2	38.021	.99909	37.986	.76760	1,117.69	857.94	.16505	6.435
3	13.1	14.738	1.00264	14.777	.77250	2,966.17	2,291.37	.41116	6.487
4	14.8	14.622	1.00231	14.656	.77046	3,009.16	2,318.15	.41366	6.476
5	5.9	42.062	.99802	41.979	.77193	1,074.70	829.61	.14798	6.356
6	5.5	41.170	.99778	41.079	.76703	1,160.68	890.28	.15016	6.319
7	6.7	14.432	1.00516	14.506	.77726	2,901.69	2,255.34	.41322	6.407
8	8.6	14.208	1.00415	14.267	.78402	2,858.70	2,241.31	.42385	6.471
9	8.1	26.260	1.00000	26.260	.76444	2,923.18	2,234.61	.40533	11.049
10	8.3	26.294	.99996	26.293	.76126	2,622.27	1,996.23	.40393	11.024
11	8.6	34.052	.99647	33.932	.76026	2,600.77	1,977.26	.40684	14.212
12	11.6	35.975	.99700	35.867	.75280	3,116.63	2,346.20	.38519	14.201
13	12.0	35.067	.99722	34.970	.74663	2,815.71	2,102.27	.39442	14.187
14	8.7	34.552	.99638	34.427	.75326	3,030.65	2,282.87	.39973	14.161
15	10.1	34.588	.99702	34.485	.75412	2,944.68	2,220.61	.40011	14.198

During these tests gas-pressure balancing valve F, figure 2, was inoperative, so that the pressure of the gas at the plane of the gas differential thermocouple thermometer, section 4–4, figure 2, was seldom the same in the large gas stream as in the small stream, due to the difference in the frictional resistance in the two gas passages. With the gas then being metered, this means that had there been no heat added by the heat exchangers the temperature of the stream at the lower pressure would have been lower than the temperature of the other stream by the amount of the Joule-Thompson effect. But since the meter was so operated that the temperature difference between the two gas streams was sensibly zero, the ratio of heat quantities added to the two gas streams was slightly greater or less than C_m, the ratio of mass flows of gas in the two streams, depending on the direction of the pressure difference. But the fundamental concept underlying the operation of the proportioning chamber involves the assumption that the ratio of the quantities of heat received by the gas streams from the water streams is equal to C'_m, the ratio of the weights of water passed through the heat exchangers. Hence, to obtain the true gas proportioning ratio, C_m, a correction computed from the Joule-Thompson coefficient for methane has been applied to the ratio of the observed water flows C'_m.

The method of computing C_m and the total mass rate of flow was as follows:

Let

C_m = the gas proportioning ratio, i. e., the ratio of the mass of gas passing through the large passage to the mass of gas passing through the small passage in a given time interval.

C'_m=ratio of weights of water passing through the heat exchangers in the same interval.

c_p(Btu/lb/°F)=specific heat of the gas at constant pressure.

c_w(Btu/lb/°F)=specific heat of water.

G=Specific gravity of the gas referred to dry air as unity.

M(lb)=total mass of water to either heat exchanger.

N=supercompressibility factor for the gas to correct for the departure from a linear relationship between pressure and density.

n=number of cycles of piston meter during test interval.

p(lb/in.^{2})=absolute static pressure of the gas.

Q(Btu)=quantity of heat transferred from the water to the gas.

T(°F)=observed temperature of the gas.

t(sec)=time interval or duration of test.

W(lb)=total mass of gas through reference meter.

w(lb/sec)=total mass rate of flow of gas.

ΔT_g(°F)=temperature change of gas.

ΔT_w(°F)=temperature change of water.

μ'(°F/in. Hg)=Joule-Thompson coefficient for the gas under the average conditions in proportioning chamber.

ρ(lb/ft^3)=density of the gas.

Subscript L refers to the large gas stream or large heat exchanger.

Subscript S refers to the small gas stream or small heat exchanger.

Subscript 1 refers to the conditions in the proportioning chamber at section 1–1, figure 2.

Subscript 4 refers to the conditions at section 4–4.

If we assume there is no heat loss by radiation or conduction, then the ratio of the total quantities of heat received by the two gas streams is given by

$$\frac{Q_L}{Q_S}=\frac{M_Lc_w\Delta T_w}{M_Sc_w\Delta T_w}=\frac{W_Lc_p\Delta T_g-W_L\mu'c_p(p_1-p_4)_L}{W_Sc_p\Delta T_g-W_S\mu'c_p(p_1-p_4)_S}, \tag{2}$$

or

$$C'_m=C_m\left[\frac{1-\mu'\dfrac{(p_1-p_4)_L}{\Delta T_g}}{1-\mu'\dfrac{(p_1-p_4)_S}{\Delta T_g}}\right]. \tag{3}$$

Since $C'_m=\dfrac{M_L}{M_S}$ and is known, equation 3 is rewritten to give

$$C_m=C'_m\left[\frac{1-\mu'\dfrac{(p_1-p_4)_S}{\Delta T_g}}{1-\mu'\dfrac{(p_1-p_4)_L}{\Delta T_g}}\right]. \tag{4}$$

From figure 2 it is evident that we may let $(p_1)_L\equiv(p_1)_S$; and if the meter were so operated that $(p_4)_S=(p_4)_L$, the term in brackets in equation 4 would reduce to 1, and we should have $C_m=C'_m$. But when $(p_4)_S\neq(p_4)_L$ the term in the brackets represents the correction factor to allow for the Joule-Thompson effect.

The composition of the gas passing through the meter was about 85 percent of methane, the remainder being higher hydrocarbons and nitrogen. The most recent data at hand [3] indicate that for methane at about 220 lb/in.^{2}, absolute, and 60° F, $\mu' = -0.026°$ F/in. Hg. The ethane will tend to raise this more than the trace of nitrogen will lower it. Hence, for the present purpose, we have used the even value

$$\mu' = -0.03° \text{ F/in. Hg.}$$

In the tests here reported neither $(p_1)_S$ nor $(p_4)_S$ was measured, but only the difference $(p_4)_S - (p_4)_L$. Hence, equation 4 cannot be solved exactly, but by the use of $(p_4)_S - (p_4)_L$ we may get a very close approximate solution. It was stated in section IV–6 that the over-all pressure drop along the proportioning chamber is restricted to 5 lb/in.^{2}, or about 10 in. Hg. Therefore, $p_1 - p_4$ will not exceed 10 in. Hg and will usually be much less. Furthermore, the lowest value of ΔT_g observed was over 5° F. Thus, the maximum value of $\frac{\mu'(p_1-p_4)}{\Delta T_g}$ in either numerator or denominator of equation 4 will not exceed 0.06, and their difference will be less than 0.01. Under these conditions a close approximation to equation 4 may be obtained by setting

$$C_m = C'_m\left(1 - \frac{\mu'}{\Delta T_g}[(p_1-p_4)_S - (p_1-p_4)_L]\right), \tag{5}$$

and since $(p_1)_S = (p_1)_L$, this reduces to

$$C_m = C'_m\left(1 + \frac{\mu'}{\Delta T_g}[(p_4)_S - (p_4)_L]\right). \tag{6}$$

It may be noted that the sign of μ' is negative, so that when $(p_4)_L < (p_4)_S$, $C_m < C'_m$.

The values of $(p_4)_S - (p_4)_L$ are given in column 5 of table 2. The values of ΔT_g and the correction term are given in columns 2 and 4 of table 3.

The density of the gas leaving the piston meter was computed by the equation

$$\rho_p = 2.6926 \frac{p_p N G}{(460+T)}, \tag{7}$$

and these values are given in column 6 of table 3.

The quantities in the remaining four columns of table 3 were computed by the equations

$$V_p = 21.494n. \tag{8}$$

$$W_S = \rho_p V_p. \tag{9}$$

$$w_S = W_S/t. \tag{10}$$

$$w = w_S(C_m + 1). \tag{11}$$

3: OBSERVED DATA FOR THE ORIFICE METER AND COMPARISON OF THE DISCHARGE COEFFICIENTS

For presenting the observed data from the orifice meter, and for computing and reducing the discharge coefficients, the following additional symbols will be used:

D (in.) = orifice diameter.

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[3] J. H. Perry and C. V. Herrmann. *Joule-Thompson effect of* CH_4, N_2, *and mixtures of these gases.* J. Phys. Chem. **39**, 1189 (Dec. 1935).

K=discharge coefficient with velocity of approach factor included.
k=ratio of specific heats of the gas assumed to be 1.28.
w_t(lb/sec)=theoretical mass rate of flow of gas through the orifice.
x=ratio of differential to upstream static pressure.
Y=expansion factor for a gaseous fluid flowing through a square-edged orifice.
β=ratio of orifice to pipe diameter.
Δp(lb/in.^{2})=differential pressure.
μ(lb(mass)/ft-sec)=viscosity of the gas; it is assumed to be 0.000 0069.[4]

Subscript 1, in connection with the orifice data, refers to the conditions at the upstream pressure tap.

The discharge coefficient of the orifice may be defined by the equation

$$K=w/w_t, \tag{12}$$

in which w is taken from the reference-meter computations as given in table 3. The theoretical mass rate of flow is computed from the equation

$$w_t=0.5249D^2\sqrt{\Delta p \rho_1}. \tag{13}$$

Equation 7 is used for computing ρ_1, values of p' being used in place of p_p. The Reynolds number, column 11, Table 4, was computed by

$$R_d=\frac{48w}{\pi D\mu}. \tag{14}$$

TABLE 4.—*Orifice meter data and calculated coefficients*

[Orifice diam.=6.000 in.; diam. ratio, β=0.5889]

1	2	3	4	5	6	7	8	9	10	11
Run	Gas temp.	Flange taps		Pipe taps		Theoretical rates of flow		Discharge coefficients		Reynolds no.
		Static pressure	Differential pressure	Static pressure	Differential pressure	Flange taps	Pipe taps	Flange taps	Pipe taps	
		p_1	Δp	p_1	Δp	w_t	w_t	K	K	$R_d \times 10^{-3}$
	° *F.*	*lb./in.²*	*lb./in.²*	*lb./in.²*	*lb./in.²*	*lb./sec.*	*lb./sec.*			
1	62. 2	220. 91	0. 3540	220. 90	0. 2254	9. 9645	7. 9507	0. 6443	0. 8075	2379
2	64. 0	220. 95	. 3547	220. 94	. 2252	9. 9754	7. 9495	. 6451	. 8095	2370
3	60. 8	222. 30	. 3542	222. 29	. 2249	10. 0527	8. 0111	. 6453	. 8098	2395
4	59. 4	222. 74	. 3543	222. 73	. 2255	10. 0533	8. 0202	. 6442	. 8075	2392
5	61. 4	219. 56	. 3506	219. 55	. 2218	9. 9062	7. 8798	. 6416	. 8066	2358
6	61. 9	217. 53	. 3499	217. 52	. 2218	9. 8556	7. 8462	. 6412	. 8054	2345
7	60. 1	220. 41	. 3510	220. 40	. 2220	9. 9686	7. 9293	. 6427	. 8080	2360
8	58. 1	221. 54	. 3526	221. 53	. 2231	10. 0585	8. 0005	. 6433	. 8088	2348
9	60. 9	218. 37	1. 0571	218. 35	. 6701	17. 2165	13. 7067	. 6418	. 8061	4090
10	60. 5	217. 14	1. 0576	217. 12	. 6706	17. 1912	13. 6882	. 6413	. 8054	4080
11	61. 3	218. 61	1. 7645	218. 58	1. 1196	22. 2350	17. 7099	. 6392	. 8025	5285
12	57. 4	216. 96	1. 7649	216. 93	1. 1197	22. 2105	17. 6899	. 6394	. 8028	5270
13	56. 8	215. 21	1. 7641	215. 18	1. 1191	22. 1194	17. 6162	. 6414	. 8053	5265
14	59. 6	215. 28	1. 7609	215. 25	1. 1173	22. 1022	17. 6050	. 6407	. 8044	5260
15	57. 8	216. 58	1. 7619	216. 55	1. 1180	22. 1683	17. 6572	. 6402	. 8041	5275

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[4] See Viscosity of Natural Gas. U. S. Bur. Mines. Tech. Pap. 555; also Appendix A, Report 2, Gas Measurement Committee, Natural Gas Dept., Am. Gas Assn.

The values of K given in columns 9 and 10, table 4, correspond to the particular conditions at the orifice under which the tests were made. In order to compare these values of K on a more nearly common basis, it was necessary to correct for the effects of expansion and viscosity (Reynolds number). This has been done, and the resulting values are presented in table 5. The expansion factors for the two pairs of pressure taps used were computed by the equations[5]

$$\text{For flange taps } Y_1=1-(0.41+0.35\,\beta^4)\frac{x}{k} \tag{15}$$

$$\text{For pipe taps } Y_1=1-[0.333+1.145(\beta^2+0.7\beta^5+12\beta^{13})]\frac{x}{k} \tag{16}$$

and are given in columns 2 and 3 of table 5. To compute the values of K which might have been obtained had there been no expansion of the gas, the observed values of K are multiplied by $1/Y_1$, and these values are given in columns 4 and 5 of table 5.

TABLE 5.—*Results of the orifice tests compared*

1	2	3	4	5	6	7	8	9	10	11
Run	Expansion factor		Coefficients for no expansion		Adjustment to K for $R_d=\infty$		Coefficients adjusted to $Y_1=1$ and $R_d=\infty$		Departures	
	Flange taps Y_1	Pipe taps Y_1	Flange taps	Pipe taps	Flange taps	Pipe taps	Flange taps K_0	Pipe taps K_0	Flange taps $0.6427-K_0$	Pipe taps $0.8070-K_0$
1	0.9994	0.9994	0.6447	0.8080	−0.0005	−0.0007	0.6442	0.8073	−0.0015	−0.0003
2	.9994	.9994	.6455	.8100	−.0005	−.0007	.6450	.8093	−.0023	−.0023
3	.9994	.9994	.6457	.8103	−.0005	−.0007	.6452	.8096	−.0025	−.0026
4	.9994	.9994	.6446	.8080	−.0005	−.0007	.6441	.8073	−.0014	−.0003
5	.9994	.9994	.6420	.8071	−.0005	−.0007	.6415	.8064	+.0012	+.0006
6	.9994	.9994	.6416	.8059	−.0005	−.0007	.6411	.8052	+.0016	+.0018
7	.9994	.9994	.6431	.8085	−.0005	−.0007	.6426	.8078	+.0001	−.0008
8	.9994	.9994	.6433	.8093	−.0005	−.0007	.6428	.8086	−.0001	−.0016
9	.9983	.9982	.6429	.8075	−.0003	−.0004	.6426	.8072	+.0001	−.0002
10	.9983	.9982	.6424	.8069	−.0003	−.0004	.6421	.8065	+.0006	+.0005
11	.9972	.9970	.6410	.8049	−.0002	−.0002	.6408	.8047	+.0019	+.0023
12	.9972	.9970	.6412	.8052	−.0002	−.0002	.6410	.8052	+.0017	+.0018
13	.9972	.9970	.6432	.8077	−.0002	−.0002	.6430	.8075	−.0003	−.0005
14	.9972	.9970	.6425	.8068	−.0002	−.0002	.6423	.8066	+.0004	+.0004
15	.9972	.9970	.6420	.8065	−.0002	−.0002	.6418	.8063	+.0009	+.0007
Averages							.6427	.8070	±.0010 ±0.16%	±.0011 ±0.14%

On the basis of a series of tests made at Ohio State University for a joint committee of the American Gas Association and the American Society of Mechanical Engineers,[6] it has been found that the discharge coefficients of orifices continue to decrease slightly even after rather high Reynolds number values are reached. By plotting values of K against $10^6/R_d$ it was possible to obtain an expression for

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[5] For an explanation of these equations see National Bureau of Standards Research Papers RP335 and RP459; also Report 2, Gas Measurement Committee, Natural Gas Dept., American Gas Association.

[6] See Report of Joint AGA-ASME Committee on Orifice Coefficients; also Prof. S. R. Beitler, *The flow of water through orifices*, Ohio State Univ. Studies, Eng. series **IV**, no. 3 (May 1935).

the value which K approaches as a limit, for any value of β, as R_d increases without limit. By using these relations, as derived from the Ohio State University tests, the adjustments to refer the values of K to the limiting condition were computed, as given in columns 6 and 7 of table 5. The values of K thus adjusted for expansion and viscosity effects and designated K_0 are given in columns 8 and 9. In columns 10 and 11 are given the differences between the individual values of K_0 and the average value for each pair of pressure taps.

VII. DISCUSSION OF TEST RESULTS AND POSSIBLE SOURCES OF ERROR

1. DISCUSSION OF TEST RESULTS

It should be noted that the variations of the individual values of the coefficients from the average, columns 8 and 9 of table 5, were obtained in the operation of the whole system and not of either one of the two meters individually.

During the first eight tests the rate of flow of the gas through the reference meter and orifice was practically constant, while the proportioning ratio was changed from 14.2:1 to 42.6:1, and the gas temperature rise changed from 5.5 to 14.7° F. Even with these changes in operating conditions, the variations in the orifice coefficients for these tests were only slightly higher than the average for the entire group of 15. Slightly greater variations were to be expected because at the lower rate of flow the orifice measurements are less reliable.

There appears to be no relation between the variations of the results and the changes in the operating conditions of the reference meter.

In studying the results of such tests it is often instructive to make an estimate of the uncertainties in the individual quantities observed. Estimates of this kind have been made for the reference- and orifice-meter system, which indicated that the departure of a test from the average might amount to 0.25 percent, which is about the maximum shown in table 5. Without giving these estimates in detail, we may state that with the exception of the specific gravity of the gas, the estimated uncertainty did not exceed 0.05 percent in any item. With the specific gravity, the best that could be expected was ± 0.2 percent, and it is doubtful whether even this accuracy was attained, although a high-grade instrument was used for its determination. One reason for this uncertainty in the gravity is that it was impossible to make more than three determinations during a test. Another and more important reason is that there were actual changes in the gravity of the gas during the duration of a test amounting in some cases to about 1 percent. That these were genuine changes, and not errors of determination, is confirmed by the fact that the routine operators of the Joliet Measurement Station obtained similar changes during approximately the same intervals, and have frequently observed such changes at other times. Since these tests were made, there has been constructed at the Joliet Measurement Station, a specific gravity apparatus with which it is believed that readings may be made at 10-minute intervals to better than 1 part in 500.

2. HEAT LOSSES

To aid in designing the meter a test was made to determine the thermal conductivity of the aluminum-foil insulation with different widths of spacing between the layers of foil. It was found that there was no advantage in having the layers of foil closer than ⅛ in. With this spacing and for the estimated temperature differences and gas pressures to be encountered, the conductivity of this type of insulation was found to be 0.31 Btu per hour per square foot per inch thickness per degree Fahrenheit difference in temperature.

For the purpose of calculating the possible heat losses two rates of flow are used. The low rate is taken as 1/50th of the listed capacity. At a line pressure of 200 lb/in^2 this will be 2,400 ft^3/hr, or 32,660 ft^3/hr when the pressure is reduced to 1 atmosphere. For the high rate the full listed rate of flow will be used.

As a basis for estimating the heat loss from the gas streams to the outside, or from one gas stream to the other, it will be assumed either that no attempt had been made, when constructing the meter, to localize the temperature change in the 16-in. shell to the band of the two encircling tubes (section X–X, figure 8), or that the upstream encircling tube is clogged. It may then be assumed that at least half of the temperature change along the 16-in. tube takes place gradually over the part surrounding the heat exchangers—a band about 11 in. wide. If the temperature of the gas rises 10° F, this will mean that at least a 5° F rise in the shell temperature is spread over this 11-in. band. To simplify the calculations, this band is divided into 1-in. bands and the heat loss from each calculated. In this way it is found that the heat loss to the outside may amount to about 0.009 percent of the total heat input to the meter.

We next consider the heat loss from the water streams entering and leaving the heat exchangers. This loss is due to the fact that the temperature of the incoming water is very much higher than the temperature of the warmed gas, and that of the outlet water is several degrees higher. From figure 8 it will be seen that the large gas stream will receive some heat from those portions of the inlet and outlet water tubes that extend across the large gas stream passage. Even here, the heat which the large gas stream receives from that portion of the total water flow supplied to the large heat exchanger is not "lost" heat. But such a transfer of heat will lower the heat content of the small water streams in tubes P and O_2, and this will be a heat loss. The amount of this loss will be proportional to the amount of water flowing in the two streams. In addition, there may be a small loss of heat from the inner ends of tubes P and O_2 to the large gas stream. As a basis for calculating the possible effect of these losses, it is again assumed the meter is operating at 1/50th its listed capacity and that the difference between the inlet water and outlet gas temperatures is 17.5° F, while that between the outlet water and outlet gas is 13.5° F. For these conditions the possible loss may amount to 0.034 percent of the heat transferred from the small water stream. This would affect the proportioning ratio by the same percentage.

Finally, the possibility of heat transfer between the large and small gas streams through the insulation between the 3- and 6-in. tubes remains to be considered. For such a flow of heat to take place there must be a temperature difference between the two streams.

In normal operation the pressures as well as the temperatures at section 4–4, figure 2, are balanced, but upstream of the pressure balancing valve F, the pressures of the two streams will not be the same at very low or very high rates of flow. Therefore, for these conditions, the temperatures of the two gas streams, upstream of valve F, will differ by the amount of the Joule-Thompson effect corresponding to the pressure difference. From the data of run 10 it is estimated that at 1/50th capacity and a 5:1 ratio the pressure difference might amount to 0.18 in. of Hg. The corresponding temperature difference would be about 0.0054° F. Taking 7 ft^2 as the area of the insulating partition between the two gas streams (which is probably high), the heat transferred between the gas streams might amount to 0.0004 percent of the heat input to the small gas stream.

Similar calculations have been made for a high rate of flow such as 120,000 ft^3/hr at a line pressure of 200 lb and using a 60:1 proportioning ratio. The results of these calculations are shown in column 3 of table 6.

TABLE 6.—*Calculated possible effects of heat losses*

1	2	3
Location of heat loss	Effect of—	
	Low rate of flow of gas	High rate of flow of gas
	%	%
Through outer insulating jacket	0.009	0.0002
From inlet and outlet water tubes	.034	.0022
Between the two gas streams	.0004	.003

If it is assumed that the effects of all of these heat losses are in the same direction, and additive, the total effects for the two rates of flow will be about 0.044 and 0.005 percent, respectively. As pointed out above, these heat-loss effects would appear as errors in the proportioning ratio.

It appears from this analysis, that if it is desired to limit the possible errors due to heat losses to ±0.05 percent, the reference meter should not be operated as a proportional meter at rates below about 32,000 ft^3/hr, referred to a pressure of 1 atmosphere. By reference to table 1 it will be seen that placing such a limitation upon the operation of the meter will result in a gap between the maximum capacity of the piston meter alone and this arbitrary minimum value for the entire meter. This gap will vary in magnitude from about 30,000 ft^3/hr at a line pressure of 14.7 lb/in.^{2} to about 5,000 ft^3/hr at a line pressure of 200 lb/in.^{2} and will vanish when the line pressure is above about 240 lb/in.^{2} At the present time a line pressure of 300 lb/in.^{2} is always available at the Joliet Measurement Station, so that by proper adjustment of line valves it is possible to operate the meter over the entire range from 400 to 2,000,000 ft^3/hr, referred to a pressure of 1 atmosphere.

3. CONCLUSION

The results of the 15 tests and the above discussion suggest that the probable uncertainties of indication of the reference meter may be numerically less than those of almost any other meter of comparable capacity and range of operating conditions. Further experience with the meter may quite possibly suggest refinements in operation that will lead to a higher precision of metering than is shown by the few tests reported here. It is hoped, therefore, that in time the meter will prove to be of considerable value to the gas industry as a reference meter of medium and large capacity.

VIII. APPENDIX A—PISTON GAGES FOR MEASURING PRESSURES

1. PISTON GAGES USED FOR MEASURING DIFFERENTIAL PRESSURES

General views of one of the two piston gages used for measuring the differential pressures across the orifice are shown in figure 13. An equal-arm balance is used for measuring the force produced by the differential pressure upon the piston. Upon one pan of the balance are placed the calibrated weights. Suspended from the other pan is a sling from which, in turn, is suspended the piston across which

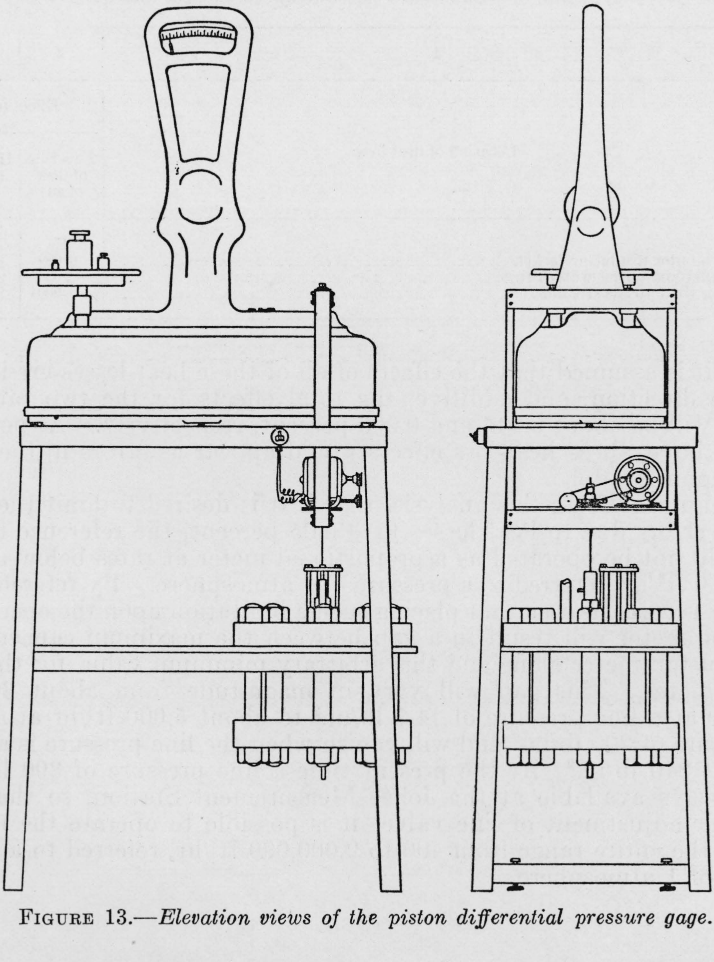

FIGURE 13.—*Elevation views of the piston differential pressure gage.*

the differential pressure is applied. The sling also carries a small motor and reduction gear for rotating the piston.

Figure 14 shows a section through the pressure chambers in which the piston and its cylinder are mounted. The chamber is firmly attached to the stand on which the balance is mounted. It is formed by a short steel cylinder 6, clamped between two carefully faced heavy flanges. This pressure chamber is capable of withstanding static pressures up to 600 lb/in^2.

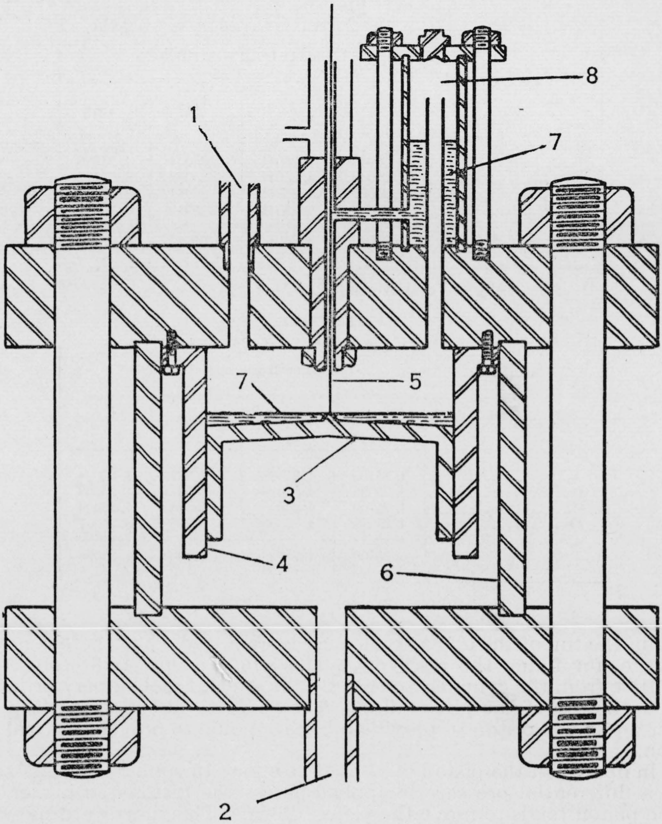

Figure 14.—*Section through pressure chamber of differential pressure gage.*

1. High-pressure connection.
2. Low-pressure connection.
3. Rotating piston.
4. Cylinder.
5. Piston drive shaft.
6. Pressure vessel.
7. Lubricating oil.
8. Oil reservoir.

Inner measuring cylinder 4 is attached to the upper flange, the two surfaces being ground to provide a gas-tight joint. This measuring cylinder is shorter than the outer cylinder, so that the annular space between the two cylinders is open to the downstream or low pressure, which is applied to the under side of the piston through the connection 2. The upstream or high pressure is communicated to the space above the piston through connection 1.

Piston 3 and the cylinder are carefully turned and ground to a very close fit. The results of measurements of the diameters of a cylinder and piston, as made with Johannsen gage blocks and indicator, are given in table 7. The piston and cylinder are made of case-hardened steel forgings.

Rod 5, by which the piston is suspended and rotated, is about 0.067 in. in diameter. It enters the pressure chamber through a lubricated sleeve or gland. Oil is supplied to this sleeve from reservoir 8. As shown by figure 14, the pressure above the piston is also applied to the surface of the oil in the reservoir. The pressure of the oil supplied to the sleeve exceeds that of the gas by the amount the surface of the oil in the reservoir is above the top of the sleeve. This slight excess of pressure is sufficient to cause a slight seepage of oil down the rod and effectively prevent any leakage of gas.

TABLE 7.—*Diameters of cylinder and piston used in one of the differential gages*

PISTON

Diameter symbol	Distance from base (inches)			
	¼	¾	1¼	1¾
A	4. 25040	4. 25041	4. 25041	4. 25039
B	4. 25040	4. 25041	4. 25042	4. 25042
C	4. 25039	4. 25041	4. 25041	4. 25040
D	4. 25040	4. 25041	4. 25042	4. 25041
	4. 25040	4. 25041	4. 25042	4. 25041

Total average----------4.25041

CYLINDER

	Distance from base (inches)			
	½	1	1½	2
A	4. 25100	4. 25098	4. 25097	4. 25098
B	4. 25099	4. 25099	4. 25097	4. 25098
C	4. 25100	4. 25099	4. 25098	4. 25099
D	4. 25099	4. 25098	4. 25098	4. 25097
	4. 25100	4. 25099	4. 25098	4. 25098

Total average----------4.25099

A plug in the top of the oil reservoir may be removed when there is no pressure on the gage, for filling the reservoir. This plug is almost directly above the pressure tube from the cylinder, so that a light mineral seal oil may be introduced directly to the top of the piston also. A layer of oil about ½ in. deep is maintained on top of the piston to provide lubrication and to prevent gas leakage past the piston.

When in operation the piston is rotated at about 15 rpm.

When a differential pressure is applied across the piston the higher pressure above the piston tends to move the piston down. This downward movement of the piston is transmitted by the supporting wire and sling to the balance, deflecting the pointer from its zero position. The magnitude of the weights required to restore the balance to zero position measures the force produced by the differential pressure upon the piston. Knowing this force and the mean area of the piston and cylinder, the differential pressure is readily computed. It was found that these differential-pressure gages responded to changes of differential pressures of as low as 1/500 in. of water.

It is necessary to take zero readings of these differential-pressure balances at the start and finish of a test, because these readings are influenced by changes in the static pressure and seepage of oil past the piston. In calculating the differential pressures observed during a test the zero reading used is obtained by correcting both observed zero readings to the average static pressure encountered during the test and then taking the mean of these corrected readings. At no time while making the tests reported in this paper did the difference between the first and second zero reading exceed 0.01 lb, which is equivalent to a differential pressure of about 0.02 in. of water.

These differential pressure balances as at present constructed can measure differential pressures up to about 50 in. of water. This range may, of course, be varied by changing the capacity of the balance, or, preferably, by changing the size of the piston and cylinder, parts 3 and 4.

When connecting pressure openings 1 and 2 to the two sides of an orifice flange, the usual 3-valve by-pass between the high and low pressure leads is, of course, included.

2. PISTON GAGES FOR MEASURING STATIC PRESSURE

For measuring static pressures a suitable piston gage was obtained by slightly modifying a high-grade dead-weight gage tester. The modifications included a restriction to the stroke of the piston so that it could not accidently be forced out of the cylinder during a test, and the installation of a large oil reservoir. The gas pressure is applied directly to the surface of the oil in the reservoir. The oil reservoir is of such size that the movements of the piston, and the leakage of oil past it during a 2-hour test, do not change the height of the oil surface by more than 0.1 in.

The piston had a diameter of about 0.5 in., but the mean effective diameter of the piston and cylinder was determined by experiment. The diameter of the piston was carefully measured, and the clearance between the piston and cylinder was determined by recording, with a chronograph, the rotational retardation of the piston when loaded with weights having known moments of inertia. The clearance could then be calculated from the known viscosity of the oil.[7]

The correction due to the difference in elevations of the bottom of the piston and the surface of the oil in the reservoir, minus the buoyancy of the piston in the oil, was included in the weight of the piston and table, giving the lowest pressure reading. The weights used were made specially to correspond to the mean effective area of the piston and cylinder, so that the reading of any pressure within the range of the gage would be correct within ±0.005 lb. While weights were provided with which pressures could be read to 0.01 lb/in.^{2}, measurements to 0.1 lb/in.^{2} were usually sufficient for the purposes of the test.

IX. APPENDIX B—DISCHARGE COEFFICIENTS OF ORIFICES DETERMINED ON THE BASIS OF THE REFERENCE METER TESTS, COMPARED WITH VALUES CALCULATED FROM EQUATIONS IN REPORT 2 OF THE GAS MEASUREMENT COMMITTEE, NATURAL GAS DEPARTMENT, AMERICAN GAS ASSOCIATION

The orifice meter used in the tests reported in this paper could be operated in series with any one of six similar orifice meters used in the regular operation of the Joliet Measurement Station. These six orifice meters and the seventh, or comparison meter, are as nearly alike in size and details of construction as it was commercially possible to make them.

Each of these six operating meters has been carefully compared with the seventh or comparison meter. On the basis of this intercomparison, the discharge coefficient of an orifice used successively in each of the six operating meter lines, has been determined from the coefficients of the comparison run orifice [8] based on the tests reported in this paper. Following these intercomparisons a 5-in. orifice was used successively in each of the six operating meters, and coefficients for it were determined. The coefficients determined by these comparisons are given in columns 5 and 7 of table 8.

Coefficients for these orifice plates in these meter runs may be computed by the equations given in report 2 of the Gas Measurement Committee, Natural Gas Department, American Gas Association. The values so computed are given in columns 6 and 8 of table 8.

In connection with such a comparison it may be noted that the equations in report 2 were based on weighed water tests, with the factors for expansion effects based on many tests with different gases. Moreover, for the sizes reported here, the report places a tolerance of ± 0.5 percent on the values of the coefficients computed from the equations. In other words, the computed coefficient for a given orifice might differ by this amount from the value obtained by a test. It will be seen that the differences between the computed coefficients and those determined by the intercomparison are well within this tolerance.

In preparing table 8 an adjustment was made to the values determined by comparison, for the effects of expansion, so that the coefficient values in all four columns represent those for an incompressible fluid.

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[7] C. H. Meyers and R. S. Jessup. *A multiple manometer and piston gages for precision measurements.* BS J. Research **6**, 1061 (1931) RP324.

[8] The orifice plate used in the comparison meter in these intercomparison tests was not the identical orifice used in the 15 tests with the reference meter, but the only known difference between the two was that of 0.0012 in diameter, which has been allowed for.

TABLE 8.—*Coefficients for the Joliet Measurement Station meters determined from the reference meter by a method of intercomparison and also by calculation*

1	2	3	4	5	6	7	8
Meter run	Pipe diameter D_1	Orifice plate no.	Orifice diameter D_2	Flange taps		Pipe taps	
				By comparison	By calculation	By comparison	By calculation
				Values of K at $R_d=4\times10^6$			
	Inch		*Inch*				
1	10. 188	7	5. 9995	0. 6437	0. 6439	0. 8094	0. 8101
2	10. 197	7	5. 9995	. 6438	. 6435	. 8097	. 8094
3	10. 192	7	5. 9995	. 6435	. 6438	. 8102	. 8098
4	10. 181	7	5. 9995	. 6442	. 6440	. 8100	. 8105
5	10. 179	7	5. 9995	. 6440	. 6441	. 8136	. 8106
6	10. 193	7	5. 9995	. 6440	. 6438	. 8107	. 8097
7	10. 186	6	5. 9988	. 6430	. 6437	. 8074	. 8100
				Values of K at $R_d=2.9\times10^6$			
1	10. 188	8	4. 9984	0. 6197	0. 6207	0. 7217	0. 7240
2	10. 197	8	4. 9984	. 6196	. 6206	. 7225	. 7238
3	10. 192	8	4. 9984	. 6198	. 6209	. 7224	. 7239
4	10. 181	3	4. 9984	. 6209	. 6206	. 7233	. 7243
5	10. 179	8	4. 9984	. 6210	. 6206	. 7248	. 7244
6	10. 186	8	4. 9984	. 6201	. 6207	. 7225	. 7240

WASHINGTON, May 27, 1936.