

A COAL-AIR FLOWMETER FOR MEASURING THE AIR-FUEL
"
RATIO IN A PULVERIZED COAL CARRYING PIPE LINE

by
Stanley M. Giddings^{core}
Hobart Speegle, Jr.

A Thesis Submitted to the Graduate Committee
in Partial Fulfillment of the Requirements
For the Degree
of

MASTER OF SCIENCE

in

Power and Fuel Engineering

Approved:

In Charge of Major Work

Head of Department

Dean of Engineering

Chairman, Graduate Committee

Virginia Polytechnic Institute

1949

145712

-1-

TABLE OF CONTENTS

	Page
Table of Figures	2
Acknowledgements	3
Introduction	5
History	7
Methods of Weighing Coal in the Power Plant	7
Previous Investigations of a Flowmeter	11
Theory of the Meter	12
Results of Tests Made at Battelle	15
The Meter Equation	16
The Investigation	19
Object	19
Design of the Coal-Air Flowmeter	20
Apparatus and Material Used	31
Methods of Procedure	37
Results	39
Sample Calculations.....	48
Discussion	51
Conclusions	56
Recommendations	57
Appendices	58
Bibliography	58
Calibration of Orifice and Nozzle	60

TABLE OF FIGURES AND TABLES

Figures		Page
1.	Detail Drawing of the Orifice	28
2.	Detail Drawing of the Nozzle	29
3-4-5-6.	Detail Drawing of the Location of Manometer Taps	30
7.	The Blower, Feeder, and Feeder Control.....	31
8.	The Blower, Feeder, Feeder Control, and Scale..	32
9.	Orifice	33
10.	Nozzle	33
11.	The Flowmeter Showing the Manometers	33
12.	The Separator.....	35
13.	Pictorial View of Apparatus.....	36
14.	Effect of Particle Size and Air-Fuel Ratio on Air-Coal Flow of Nozzle.....	45
15.	Effect of Particle Size and Air-Fuel Ratio on Air Flow Indication of Orifice.....	46
16.	Correction Curve for Indicated Coal Flow.....	47
Tables		
1.	Data Sheet, Set A	39
2.	Data Sheet, Set B	40
3.	Data Sheet, Set C	41
4.	Result Sheet, Set A	42
5.	Result Sheet, Set B	43
6.	Result Sheet, Set C	44

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Edward Williams and Mr. Charles Dewey, Jr., Test Engineers, both of the Duke Power Company; Mr. Edward Painter and Mr. Thigpen, superintendent, both of the Glyn Lyn Power Station of the Appalachian Electric Power Company; and Mr. E. E. Clapper, Superintendent of the Logan Station of the Appalachian Electric Power Company for supplying the information about their respective plants. This information formed the basis of the design for the test flowmeter used in this investigation.

The authors also wish to thank Mr. R. B. Engdahl, Supervisor, Battelle Memorial Institute, Columbus, Ohio, for his many suggestions; Professor F. M. Morris of the Mining Engineering Department for the use of the Mining Laboratory and for the loan of a coal feeder; and Professor H. S. Miles, Jr. for providing space in the Mechanical Laboratory for setting up the test apparatus.

An acknowledgement is also due Mr. Frank Grissom of the Mechanical Laboratory for his assistance during the construction of the apparatus.

The authors are especially indebted to Mr. Charles G. Giddings of the Newport News Shipbuilding and Dry Dock Company for providing the nozzle, and to Mr. J. C. Fox, Electrical Engineer of the Virginian Railway and Mr. Shands, Superintendent of the Virginian Railway Power Plant for supplying 1000 pounds of

flyash. If it had not been for the interests of these three men, this investigation may not have been possible.

And last, the authors want to express their appreciation to their wives, Margaret Giddings and Jane Speegle for their untiring assistance in taking manometer readings during the running of all the tests.

INTRODUCTION

Materials handling is a problem in every type of industry. "It has been said that today the greatest opportunities for the reduction of industrial costs and for increased manufacturing efficiency lie in the more economical handling and transporting of materials rather than in the more economical manufacturing and processing of materials (1)." Every element going into a process and the finished product emerging has to be moved, counted or weighed, and stored. The Power Industry is not an exception. Fuel has to be moved to the power plant and weighed, stored, reweighed, restored in a hopper, and then transferred to the boiler. Ashes have to be removed and carried away from the plant. Large quantities of air have to be forced into the boiler. Steam has to be piped to the turbines, and the electrical energy has to be distributed to the consumer. All of this constitutes a complex materials handling problem.

In the power plant, the most critical transporting problem is that of moving the fuel. The production of steam and electrical energy depends on adequate and steady flow of fuel to the boiler. In power plants that utilize coal as the principle fuel, an adequate record has to be kept of the quantity of the flow of coal. This has to be done to insure complete material control. To do this, the coal has to be weighed. The subject of this thesis deals with this one item in the

problem of coal handling in the modern power plant. Coal coming into the power plant is often weighed as it is unloaded from the coal cars. In some plants the coal is again weighed on a conveyer belt or by a weigh larry. At the present time, no method is used in the power plant to indicate the flow of coal and air and indicate the air-fuel ratio after the coal has been pulverized and is being carried to the burners. Such a device is the object of the investigation that this thesis is reporting. This device is a coal-air flowmeter that could be placed in each line carrying pulverized coal and primary air for each burner. The operator could know what the air-fuel ratio and the coal-air flow to each burner was at all times. The authors feel the development of such a meter will result in a more exact control over combustion at a time when in steam generator design, control is a necessity rather than a convenience. There are many other applications of the meter, such as the measurement of finely divided solids flowing in gas streams such as those found in some catalytic cracking processes.

The authors in undertaking this investigation are primarily interested in the control of flow in pulverized-coal-burning equipment in the power industry.

HISTORY

Methods of Weighing Coal in Power Plants

There are many different ways of weighing coal in the power plant. Of these, six are the most commonly used today.

The most common method of weighing coal in plants having stoker fired furnaces is by the weigh larry. The weigh larry is a traveling hopper that moves on an overhead track back and forth in front of the different boilers in the plant. The average weigh larry has a capacity of about 2000 lbs. The hopper is connected to a balance arm by a linkage such that any weight up to the hopper capacity can be observed by balancing the arm. The hopper forms the same function as the platform on a simple platform scales. A motor is generally used to move the larry. Coal can be taken from any part of an overhead bunker, weighed, and transferred to any boiler in the plant along the bunker line. This type of weighing device is used principally in plants having stoker fired boiler furnaces.

Another method of finding the flow of coal that can be utilized in coal chutes, is the Bailey Coal Meter (2). The primary element of the meter is a section of a helix mounted on the center line of a chute and geared to a revolution counter. After calibrating, the rotation of the helix will measure the weight of coal flowing through the chute. If the chute should empty as when the coal hangs up above the meter, the helix will continue to spin. The readings are valid only for a continuing flow. The chute must be within 20° of the

vertical position and the coal must be sized.

A third type of weighing device is the Batch type weigher. It generally consists of a counter-weighted hopper fed by a short belt feeder. When the weight of coal in the hopper balances to the adjusted value, the hopper drops slightly, stopping the feed and opening the hopper discharge gate. When the hopper is empty, the gate closes and the cycle repeats itself. Each drop is recorded on a counter. The standard sizes range from hopper capacities of 200 to 1000 lbs., and the machine operates within 0.5 per cent accuracy under average conditions. If the coal flow should be blocked, the cycle stops until the receiving hopper is clear. The scale operates only at a rate called for by the consumption. In many pulverized fuel plants, this type of weigher is used to weigh the coal just before it enters the pulverizing mills.

A fourth method of weighing coal is the poidometer. The operation of this instrument depends on the movement of a constant volume ribbon of material. A short belt supported at the exact center of its length, by a scale beam, which as it lifts or falls lowers and raises a gate controlling the flow from the feed hopper, thus leveling the stream on the belt to a depth or weight per foot of belt as determined by setting of the scale. If the belt should hang up, the belt will automatically stop, and restarts automatically when flow resumes. The meter records the number of feet traveled by the loaded belt and this multiplied by the weight at which

the scale beam has been set registers the pounds of coal delivered.

Another similar weighing device is the feeder weigher. This instrument also works on the principle of a constant amount of material traveling on a belt. A short pivoted belt takes the material from a hopper at a rate controlled by a weighted lever, which opens or closes the hopper gate depending on the load on the belt. The rate of feed is adjustable either by adjusting the counter weight or by variable speed drive. The belt maintains a constant rate of discharge by weight and a revolution counter records the belt travel.

A sixth weighing instrument that is used in the power plant is the weightometer. This type of weigher is also used in conjunction with a belt feed system. An integrated disk has crowned rollers around the periphery and is free to tilt under the pull of the balance beam of the weigher. A narrow belt that encircles the disk is driven by the coal carrying belt. The mechanism is adjusted so that when the conveyer is under no load the disk will not rotate because it will be at a 90° angle with the direction of travel of the small belt. Any load on the conveyer belt tilts the disk and it rotates slowly, depending on the degree of tilt, which in turn depends on the load on the conveyer. The rotation of the disk is a measure of the weight of material passing over the suspended section of the conveyer belt. The rotating disk registers the total weight conveyed.

Most modern power plants use one of the above methods to weigh coal. The Glyn Lyn Station of the Appalachian Electric Company and the Tidd Plant of the Ohio Power Company both use batch type weighers placed in the coal handling system just before the coal enters the pulverizing mills (3). The Charlotte Station of the Duke Power Company utilizes weightometers. One weightometer is used with each bunker and pulverizing mill. The new Philip Sporn Station now under construction that will be a joint station of the Appalachian Electric Power Company and the Ohio Power Company does not have any method to weigh coal going to each boiler (4). This plant, when finished, will have a generating capacity of 250,000 KW. The coal is weighed on a belt entering the plant. No direct method is used for determining the coal flow to each boiler. Each boiler will have ten burners. The new section on the Twin Branch Station in Chicago has a batch type weigher before each pulverizing mill (5). Each boiler has eight burners supplied by four pulverizing mills.

As far as known, no method is in use today for measuring the flow of coal in the power plant after pulverization. In most plants the coal is weighed the last time just before entering the pulverizing mills. Each pulverizing mill may supply coal from two to six different burners on a single boiler. The assumption is always made by power plant engineers that the flow of coal and air to each burner is equal. The need for a meter that would indicate the flow of coal, the

flow of air, and the air-fuel ratio in each burner pipe line can be fully appreciated. Such a meter would give better control over combustion in the furnace. The boiler operator could know the air fuel ratio and the flow of coal going to each burner at all times. Some boilers that utilize pulverized coal may have as many as 20 burners. It is not unreasonable to assume that the air-fuel ratio in each burner pipe line will not be equal. It is feasible that a burner located around the boiler from the pulverizing mills will receive less coal than a burner located close to the mill.

Previous Investigations of A Coal-Air Flowmeter

Several devices have been tried for measuring the flow of solid particles being carried in an air stream. A swinging vane suspending from a horizontal bar has been tried. It is reported that several such devices have been used in the Witwatersrand gold mines in South Africa (6). During the course of research on this problem at Battelle Memorial Institute in Columbus, Ohio, it was proposed that two swinging vanes be placed in the coal air carrying line, one before the introduction of the coal and one after the coal has been forced into the air stream. The difference in the angle of inclination of the two vanes would indicate the flow of coal. The effect of the coal on the second swinging vane could not be measured by a change in angle of swing.

A photo electric meter was being investigated at this time also at Battelle (6). This meter employed a nozzle that

converged the air and coal stream such that a light beam could be directed across this stream. The meter was to operate on the principle that coal passing in the stream would vary the light intensity of the beam falling on the photoelectric cell. The nozzle was to measure the flow of air. During this investigation it was found that the pressure differential across the nozzle was affected by the presence of coal in the air stream. A conventional orifice was also tried and it was found that the pressure differential was only slightly affected by the introduction of coal dust in the air stream. Utilizing a nozzle and an orifice in series, Messrs. H. M. Carlson, P. M. Frazier, and R. B. Engdahl of the Battelle Memorial Institute built a laboratory model of the coal-air flowmeter. They reported their findings in a paper entitled, A Meter for Flowing Mixtures of Air and Pulverized Coal appearing in the February, 1948 Transactions of the ASME.

Theory of the Meter

Messrs. Carlson, Frazier, and Engdahl could not advance a complete and satisfactory theory for the action of the meter. According to them, the simplest theory is that the particles do not have time to accelerate in the abrupt contraction of the orifice, hence the passage is not indicated by the orifice differential. An orifice measures acceleration alone. They therefore, contend that since a nozzle will measure a coal-air mixture, the particles do have time to accelerate in a gradual constriction such as is characteristic of a nozzle.

As another line of thought, they bring out the deduction of Stodola on the lag of suspended particles of wet steam that form at the throat of a nozzle and lag behind the main stream of steam because of their inertia. However, this well known effect did not indicate the difference between the action of an orifice and a nozzle.

An additional effect advanced by Messrs. Carlson, Frazier, and Engdahl, is that the lag of particles in the accelerating stream may distort the flow pattern through the orifice. The flow pattern is normally established by the orifice face and is maintained by the force of the moving stream. On the other hand a nozzle has walls that definitely form the flow pattern. In the case of an orifice, the dust particles may form a concentration around the face, distort the flow pattern, and shift the vena-contracta. This could either increase or decrease the indicated flow rate.

Mr. J. M. Cunningham of the Gulf Research and Development Company, Pittsburgh, Pennsylvania, wrote in the discussion of the paper written by Messrs. Carlson, Frazier, and Engdahl that a difference in the acceleration of the coal particles and that of the air at the entrance of the orifice would produce a concentration and thus an accumulation of coal at the mouth of the orifice. He therefore, concludes that the orifice readings should give an indication of the coal flow, rather than the nozzle which is contrary to actual experimental results.

Mr. Cunningham advances the theory that the nozzle pressure differential is affected by the presence of coal because of the friction and viscosity effects of the mixture flowing. As Mr. Cunningham wrote, "While friction and viscosity effects are considered indirectly in the flow coefficients of the meter elements, the friction effects will be more pronounced in a nozzle where the fluid completely fills its boundaries, whereas the fluid in the flow through an orifice makes contact only at the entrance."

Messrs. W. E. Young, J. T. Perry, and A. E. Hershey of the Research Laboratories of the Westinghouse Electric Corporation have also built a coal flowmeter in connection with their investigations of feeding and burning pulverized coal. Their meter was built in a three-quarter inch pipe line. They experienced trouble in keeping the nozzle and orifice free of coal accumulation. Messrs. Young, Perry, and Hershey contend that there is no distortion of the flow lines through an orifice as Messrs. Carlson, Frazier, and Engdahl have advanced as a possible theory. According to photographs of path lines approaching and passing through orifices and nozzles, the difference in the shape of the path lines are relatively small for the two different elements (7).

In relation to Mr. Cunningham's friction theory, Mr. Engdahl wrote later that nozzles with straight throat lengths of five to ten diameters were used in the meter. No difference in meter performance could be noticed between the use of the long

and short throated nozzles. Mr. Engdahl believes that if friction were an important factor, there would have been a marked difference in meter performance while using two different length nozzles.

Results of Tests Made at Battelle

Messrs. Carlson, Frazier, and Engdahl constructed coal-air flowmeters in 3/4 inch, 1 1/2 inch, 2 inch, and 4 inch nominal pipe diameter pipe lines. They found that pipe size in the above range had no effect on the performance of the meter. They did not make a complete study of the effect of different nozzle to pipe diameter ratios. The range of ratios they used in tests with the orifice was 0.6 to 0.75. Tests were run on the meter using different coal fineness. As finer coal was passed through the meter, the flow indication became smaller than the actual flow. The opposite was true for larger particle size coal. Eighty-five per cent through 200 mesh gave readings that closely approximated the actual coal flow. The maximum per cent error for different particle size was not over 7 per cent for a range of particle size of from 75 per cent to 92 per cent through 200 mesh.

The tests of the meter have given accurate results within plus or minus 5 per cent over a range of air fuel ratios of 3/4 to 1 to 2 to 1.

Some trouble was experienced by the accumulation of coal on the edge of the orifice. This problem was overcome by bonding a layer of rubber on the face of the orifice.

The test meters were built in lines operating at 100 psi and lines operating at 15 psi. Except for manometer line leakage, the meter performance was good. The leaks in the manometer lines caused coal to be drawn into the lines and clogging them.

The meter was found to work equally well in a vertical line as in a horizontal pipe line.

Further investigation of the meter at Battelle was completely stopped in February, 1948 (8). As far as known, no further work has been done on the development of the meter up to this time.

The nozzle in the meter at Battelle utilized throat taps. Messrs. Carlson, Frazier and Engdahl stated that they believed pipe taps would give the same results.

THE METER EQUATION

The authors feel that the complete derivation of the meter equation should appear in this thesis. Therefore, the meter equation is derived below as taken directly from the paper by Messrs. Carlson, Frazier, and Engdahl at Battelle Memorial Institute.

After it was observed that the orifice differential was not greatly affected by the presence of coal particles passing in the line, whereas the nozzle differential was affected, the two elements were placed in series to measure both the flow of air and coal at any point in a coal-air line. This method of measuring solids in an air or gas stream was believed to be new, and a patent application has been filed. Further algebraical manipulations showed that by using the calculations of both of these elements,

together with a minor simplifying assumption, it was possible to obtain a simple mathematical formula which enables the direct calculation of the amount of coal flowing without knowing the density of the mixture flowing, as would be required if the nozzle alone were used. The derivation of this formula follows.

The equation for gravimetric flow through a constriction is

$$W = e C A f \sqrt{2g\Delta h} \dots \dots \dots (1)$$

where

- W = weight rate of flow of the fluid, lb. per hour
- e = fluid density, lb per cu ft
- C = coefficient of discharge
- A = area of constriction, sq ft
- f = velocity of approach factor
- g = acceleration of gravity, fps
- h = differential head in feet of fluid

If we now assume the mixture of coal and air flowing through the constriction to be a homogeneous fluid, and assume that C, the coefficient of discharge, remains constant for fluids of different densities, only the factor Δh in the equation will change as coal is added, however

$$\Delta h = \frac{1w}{12e}$$

where

- 1 = pressure drop across constriction in inches of manometer fluid
- w = density of manometer fluid used in measuring pressure differential, lb per cu ft

The formula then becomes

$$W = e C A f \sqrt{\frac{2g1w}{12e}} \dots \dots \dots (2)$$

which equals

$$W = C A f \sqrt{\frac{2g1w}{12}} \sqrt{e} \dots \dots \dots (3)$$

Now for a coal-air mixture passing through the constriction

$$e = \frac{(W_a + W_c)}{W_a} e_a \dots \dots \dots (4)$$

where

- ρ = density of mixture, lb per cu ft
- ρ_a = density of air, lb per cu ft
- W_a = weight rate of air flow, lb per hr
- W_c = weight rate of coal flow, lb per hr

If it is assumed for the density of the mixture herein considered that the coal occupies no space, an assumption that makes less than 0.25 per cent error in the calculations, Equations 3 and 4 can be combined to give

$$W_a \neq W_c = C A f \sqrt{\frac{2g i w \rho_a}{12}} \sqrt{\frac{W_a \neq W_c}{W_a}} \dots (5)$$

which in turn equals

$$W_a \neq W_c = \rho_a C A f \sqrt{\frac{2g i w}{12}} \sqrt{\frac{W_a \neq W_c}{W_a}} \dots (6)$$

Squaring both sides, we have

$$(W_a \neq W_c)^2 = \left(\rho_a C A f \sqrt{\frac{2g i w}{12}} \right)^2 \frac{(W_a \neq W_c)}{W_a}$$

or

$$W_a (W_a \neq W_c) = \left(\rho_a C A f \sqrt{\frac{2g i w}{12}} \right)^2$$

Thus the coal rate is

$$W_c = \frac{\left(\rho_a C A f \sqrt{\frac{2g i w}{12}} \right)^2}{W_a} - W_a \dots (7)$$

The expression in parentheses in Equation 7 is a fictitious "Mixture flow," where i is the pressure drop for the nozzle passing air plus coal, but the density used in the expression is not that of the mixture, but of the air alone. It is computed from the measurements as though air alone were flowing. If this expression is replaced by W_{an} , Equation 7 becomes

$$W_c = \frac{W_{an}^2}{W_a} - W_a \dots (8)$$

W_a is obtained very nearly by using an orifice with the usual flow formula in the mixed flow line. Thus the weight rate of coal flow may be calculated by using the flow equation for both orifice and nozzle as though air alone were flowing, and substituting these two calculated rates in Equation 8.

THE INVESTIGATION

The Object

The object of this thesis is to design, build, and calibrate a coal-air flowmeter to operate in a pipe line through which a mixture of powdered coal and air are being blown; and to investigate the accuracy of the meter while operating at different air-fuel ratios.

It is the authors intention to test the coal-air flowmeter in a pipe line in which conditions exist that closely simulate actual conditions that exist in power plants burning pulverized coal. The flow characteristics of the meter will, as near as possible, be the same as may be found in a typical industrial application. For this reason, a large size pipe line will be used and the air pressure in the pipe line will be relatively low.

It is believed that a coal-air flowmeter has not before this time been investigated in a large pipe and utilizing low pressures.

Because of conditions over which the authors had no control, flyash had to be substituted for coal for the testing of the coal-air flowmeter. The authors are mainly interested in the measurement of the flow of coal and therefore have referred to the meter as a coal flowmeter throughout this thesis. The authors believe the use of flyash as the test medium will demonstrate the usefulness of the meter to measure the flow

of any type of finely divided particle being carried by an air stream.

Design of the Coal-Air Flowmeter

A questionnaire was mailed to the Glyn Lyn and Logan Station of the Appalachian Electric Power Company and the Charlotte Station of the Duke Power Company. The following questions were asked of the superintendents of each of the above stations:

1. The approximate coal particle size after leaving pulverizing mills;

Answers received from Glyn Lyn, Logan and Duke were, 80-90 per cent through 200 mesh screen; 79 per cent through 200 mesh screen, and 78.6 per cent through 200 mesh screen.

2. The size of the line supplying primary air and pulverized coal to each burner;

Answers received from Glyn Lyn, Logan, and Duke were, 10 inch lines.

3. The pressure in the above line;

Answers received from Glyn Lyn, Logan, and Duke were, 2 inches of water, 6.7 inches of water and 3 inches of water.

4. The air-fuel ratio in the above line;

Answers received from Glyn Lyn, Logan, and Duke were, not known, cannot be determined, and approximately 1.5 lb air/lb coal.

5. The approximate coal flow in lbs/hr in the above line;

Answers received from Glyn Lyn, Logan and Duke were 6,250 lbs/hr, 5200 lbs/hr and 3000 lbs/hr to each burner.

6. The method (if any is used) for finding the flow of coal going to each burner;

Answers received from Glyn Lyn, Logan, and Duke were all three answered $\frac{\text{output of mill}}{\text{number of burners}}$

Using the approximate air-fuel ratio of 1.5 given by the Duke Power Company, the velocity of the coal-air mixture in a burner pipe line may be calculated.

The coal flow given by the Duke Power Company is 3000 lb per hour per burner. That will be $\frac{1.5 \times 3000}{3600}$ or 1.25 lb of air per second per burner. That in turn is equal to $\frac{1.25}{.075}$ or 16.68 cfs of air flowing. The area of a ten inch pipe line is 0.546 square feet. Therefore, the velocity will be $\frac{16.68}{0.546}$ or 30.5 ft per second.

If an air-fuel ratio of 1.5 is assumed for the Glyn Lyn and Logan Stations, the approximate velocity may also be calculated. If this be done, the velocities for the two plants will be 49 feet per second and 63 feet per second.

From curves on the velocity of flame propagation with powdered coal, it can be seen that the highest value for the coal plotted is 44 feet per second (9). The authors chose an average of 50 feet per second as the design velocity for test meter.

Because it was desired to test the meter in a larger pipe size than has been already done, an eight inch pipe size was chosen.

Inside diameter of a standard eight inch pipe is 8.08 in.
Area of pipe $\frac{\pi d^2}{4} = \frac{3.14 (8.08)^2}{4 \times (12)^2} = 0.356$ sq ft.

Volume of flow $Q = AxV$

Where $A =$ Area of flow, sq ft.

$V =$ Velocity in pipe, ft per sec.

$Q = 50 \times 0.356 = 17.8$ cu ft per sec.

From $PV = WRT$, the volume per lb can be calculated.

Where $W = 1$ lb.

$R = 53.3$ for air.

$T = 460 + 70 = 530^\circ R$.

$P = 28$ in. of Mercury $\times 0.491$.

Specific Volume $= \frac{53.3 \times 530}{144 \times 28 \times 0.491} = 14.3$ cu ft per lb.

$\rho = \frac{1}{V} = \frac{1}{14.3}$

$\rho = 0.070$ lb per cu ft.

The flow of air W_a , lb per sec $= Q \times \rho$

$= 17.8 \times 0.070$

$W_a = 1.25$ lb per sec.

or $1.25 \times 3600 = 4500$ lb per hr.

For a minimum pressure drop an orifice-to-pipe diameter ratio of 0.70 was chosen. This gives an orifice diameter of 8.08×0.7 or 5.656 inches.

The throat diameter to pipe diameter ratio for the nozzle

was chosen as 0.65. This gives the nozzle throat diameter as 0.65 x 8.08 or 5.25 inches.

Calculation of the Reynolds number for these conditions gives the following:

$$\text{For the orifice, } R_o = \frac{48w}{D_o U \pi}$$

Where w = flow, 1.25 lb per sec.

D_o = diameter of orifice, 5.649 inches.

u = absolute viscosity, 12.75×10^{-6} , lb/ft/sec
from figure 14, page 25 (10).

$$R_o = \frac{48 \times 1.25}{3.14 \times 5.649 \times 12.25 \times 10^{-6}}$$

$$R_o = 276,000$$

$$\text{For the nozzle } R_n = \frac{48 \times w}{D_n U \pi}$$

Where D_n = Diameter of the throat, 5.25 inches

$$R_n = \frac{48 \times 1.25}{3.14 \times 5.25 \times 12.25 \times 10^{-6}}$$

$$R_n = 294,000$$

From figure 31, page 44 (10) it can be seen these Reynolds numbers for flow are sufficiently high to give constant flow coefficients. From page 54 (10) the flow coefficients K for the orifice is found to be 0.7025. From page 44 (10) the nozzle coefficients is found to be 1.085. Both these coefficients include the velocity of approach factor.

The practical formula which is derived from the fundamental flow formula gives fluid flow on the weight basis as follows:

$$w = 413.3KD \sqrt{\frac{1B}{T}}$$

Where - B = Barometer reading, inches of Mercury

K = flow coefficient.

W = flow, lb per hr.

i = differential across element, inches of water.

T = temperature of fluid flowing, °R abs.

D = diameter of the constriction of the element, in.

Therefore flow for the orifice, $W_o = 413.3 \times 0.7025 \times 5.649^2 \sqrt{\frac{1B}{T}}$

$$W_o = 9250 \sqrt{\frac{1B}{T}}$$

By design $W_a = W_o = 4500$ lb per hr, since $Q = 1.25$ lb per sec.

$$\text{Therefore } 4500 = 9250 \sqrt{\frac{1 \times 28}{530}}$$

$i = 4.5$ inches of water drop across the orifice.

For the nozzle it is first necessary to solve for W_{an} .

For an air-fuel ratio of one to one, the coal flow will be 4500 lb per hr..

$$W_o = \frac{(W_{an})^2}{W_a} - W_a$$

$$4500 = \frac{(W_{an})^2}{4500} - 4500$$

$$(4500)^2 = W_{an}^2 - (4500)^2$$

$$(W_{an})^2 = (4500)^2 + (4500)^2$$

$$W_{an} = 6360$$

The flow through the nozzle is given by the expression

$$W_n = 413.3 K_n D^2 \sqrt{\frac{1B}{T}} \text{ or } 413.3 \times 1.085 \times 5.25^2 \sqrt{\frac{1B}{T}}$$

$$W_n = 12,310 \sqrt{\frac{1 \times 28}{530}}$$

$$\text{But } W_{an} = W_n = 6360 = 12310 \sqrt{\frac{1 \times 28}{530}}$$

$$0.27 = \frac{1 \times 28}{530}$$

$i = 5.10$ inches of water differential across the
the nozzle.

The overall pressure drop through the meter will now be determined. The pressure loss through nozzles and orifices can be approximately be found from the expression.

$$\Delta P' = \Delta P'' \frac{1 - K (D2/D)^2}{1 \mp K (D2/D)^2} \quad \text{Page 17, paragraph 56 (10).}$$

Where $\Delta P'$ pressure loss in inches of water.

$\Delta P''$ differential pressure across element in
inches of water.

$D2/D$ - ratio of diameters.

K = flow coefficient.

For the orifice:

$$\Delta P'_o = 4.5 \frac{1 - 0.7025 (5.656/8.08)^2}{1 \mp 0.7025 (5.656/8.08)^2}$$

$$\Delta P'_o = 4.5 \frac{1 - 0.345}{1 \mp 0.345}$$

$$\Delta P'_o = 4.5 \times 0.487$$

$\Delta P'_o = 2.2$ inches of water loss through the orifice.

For the nozzle:

$$\Delta P'_n = 5.1 \frac{1 - 1.085 (5.25/8.08)^2}{1 \mp 1.085 (5.25/8.08)^2}$$

$$\Delta p'_n = 5.1 \frac{1 - 0.458}{1 + 0.458}$$

$$\Delta p'_n = 5.1 \times 0.372$$

$$\Delta p'_n = 1.9 \text{ inches of water loss through the nozzle.}$$

The total pressure loss through the meter will equal approximately the sum of the pressure losses through each element. Therefore, $p'_m = \Delta p'_o + \Delta p'_n$

$$\text{or } p'_m = 2.2 + 1.9$$

$p'_m = 4.1$ inches of pressure loss through the meter.

The additional power required to overcome the pressure loss due to the meter being in the line can now be calculated.

$$\text{H. P.} = \frac{W P'_m H}{550}$$

Where W = weight of air and coal flowing, lb per sec.

H = feet of air equivalent to one foot of water pressure.

$$\text{H. P.} = \frac{2.5 \times (4.1/12) \times 894}{550}$$

$$\text{H. P.} = 1.385$$

For the purpose of the test of the above coal-air flowmeter, flyash and air will be blown through a pipe line in which the meter has been installed, then through a separator from which the air will be emitted to the atmosphere. The blower will be required to deliver about 1075 cubic feet of air per minute. Assuming 10 inches of water pressure loss due to pipe friction and the separator, the total pressure loss through the test

apparatus will be $10 \neq p'_m$ or $10 \neq 4.1$ which equals 14.1 inches of water. Therefore, the power required to drive the blower of the test apparatus will be $\frac{WH}{550}$

Where $W = 2.50$ lbs per second.

$$H = \frac{14.1}{12} \times 894 \text{ feet of air}$$

$$HP = \frac{2.50 \times 14.1/12 \times 894}{550}$$

$HP = 4.775$ or say a 5 hp motor.

The nozzle was designed according to the specifications of the International Standards Association as found in the Power Test Codes (10). The orifice was designed according to specifications given in figure 32 of Power Test Codes (11).

Detail drawings of the orifice and nozzle, figure 1 and figure 2, appear on the following two pages. Figures 4, 5, 6, and 7, show the pipe lengths used and the position of the taps.

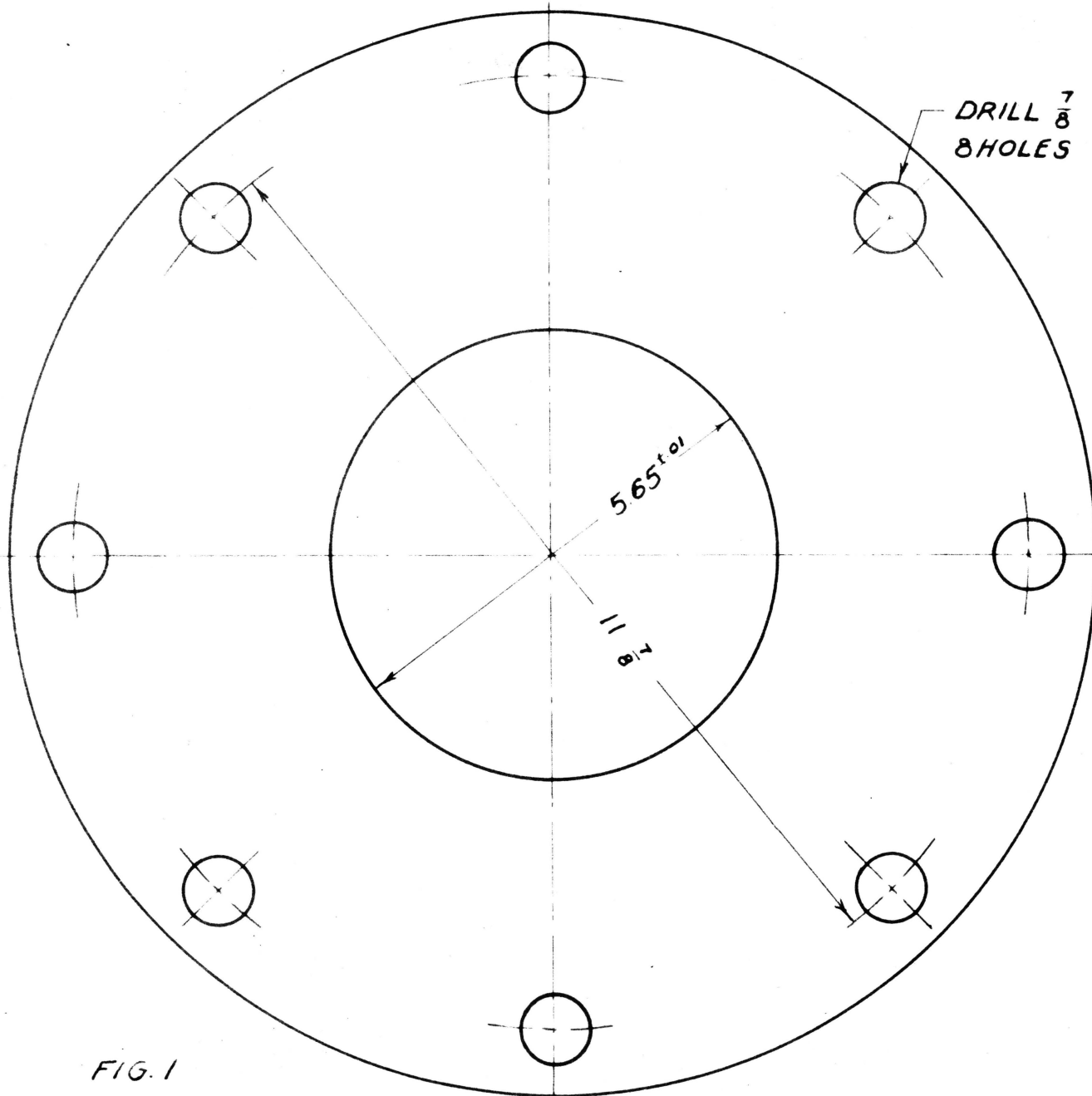
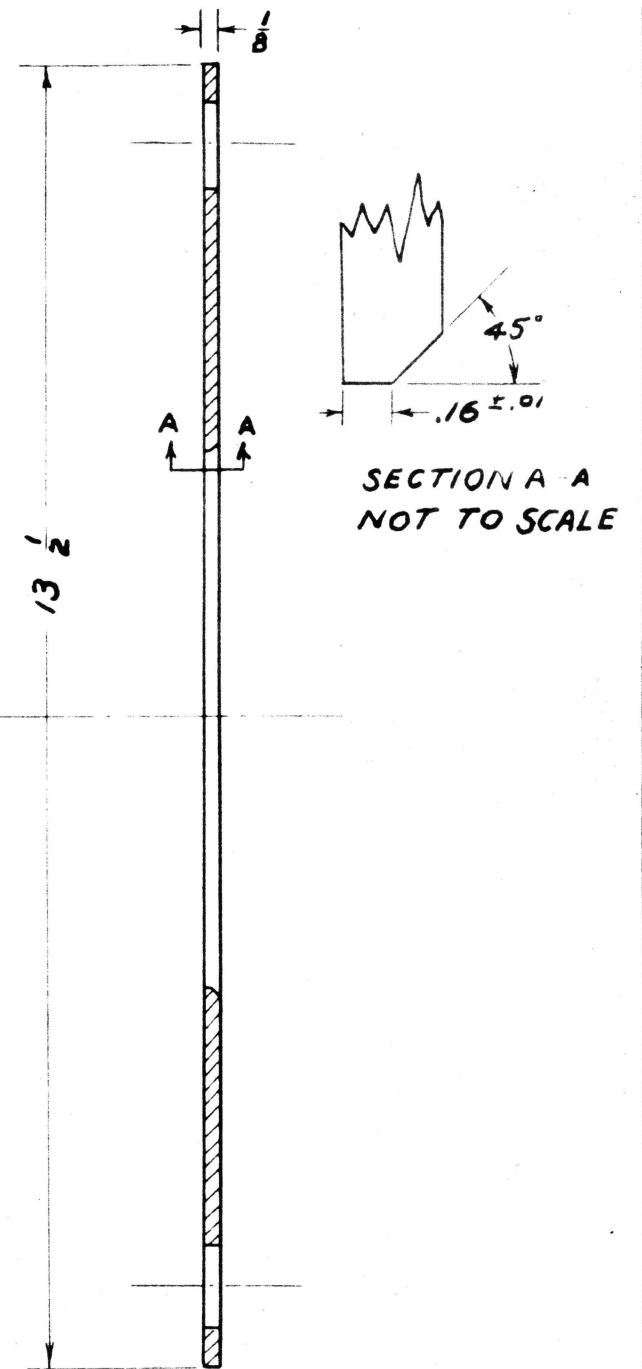


FIG. 1
ORIFICE DESIGN

SCALE 6" = 1'-0"



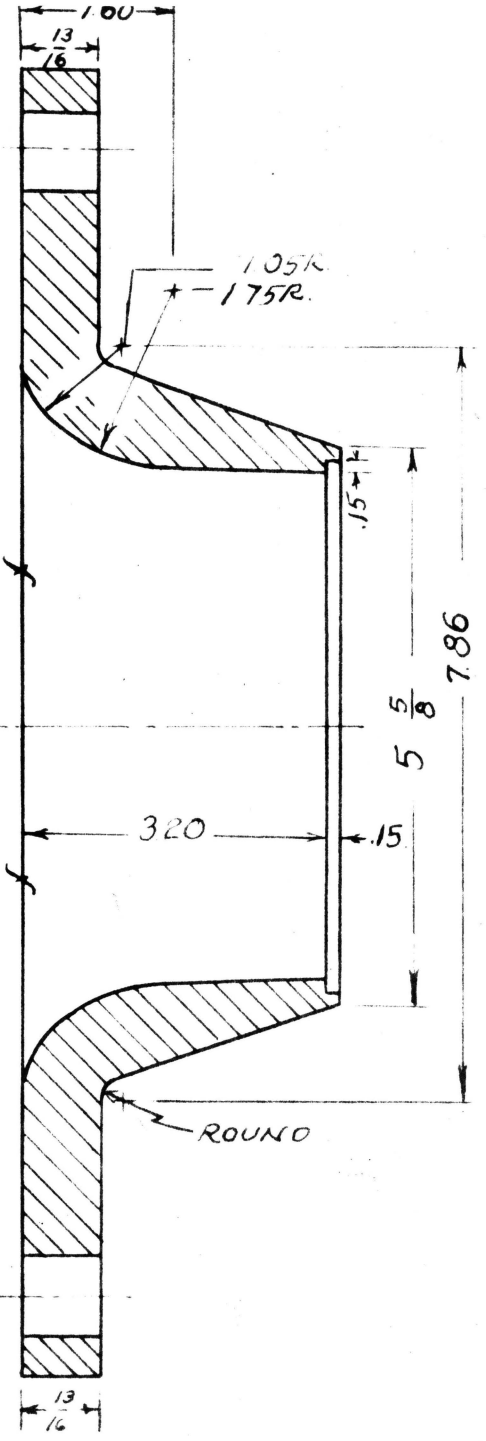
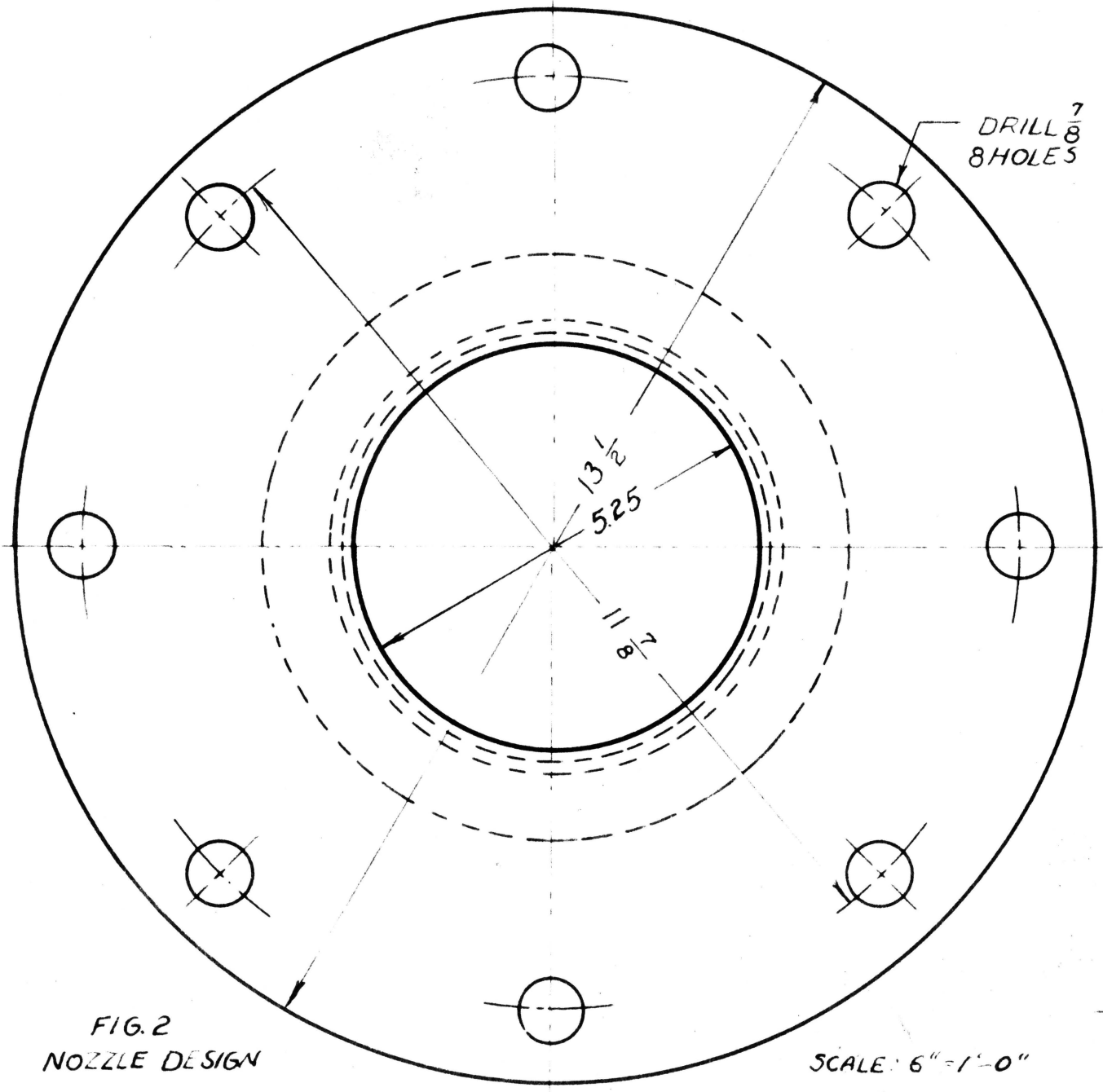
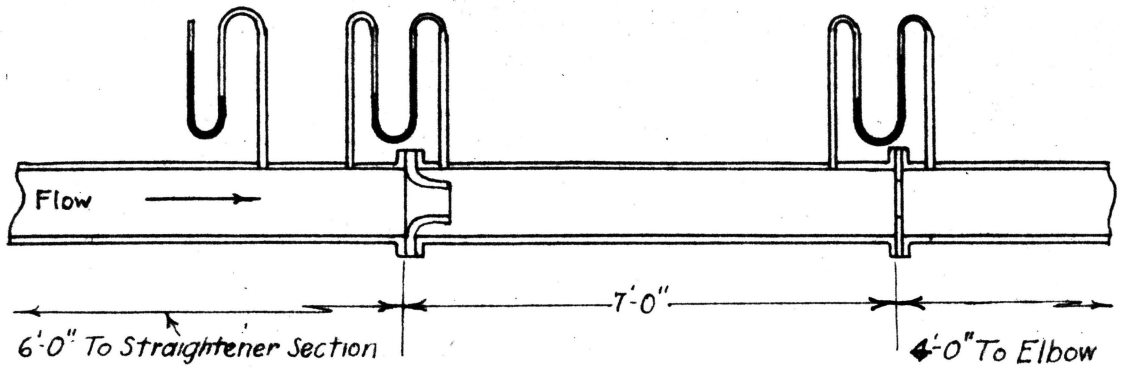


FIG. 2
NOZZLE DESIGN

SCALE: 6" = 1'-0"



Test Pipe - 8.08" I.D. Cast Iron

Figure 3.

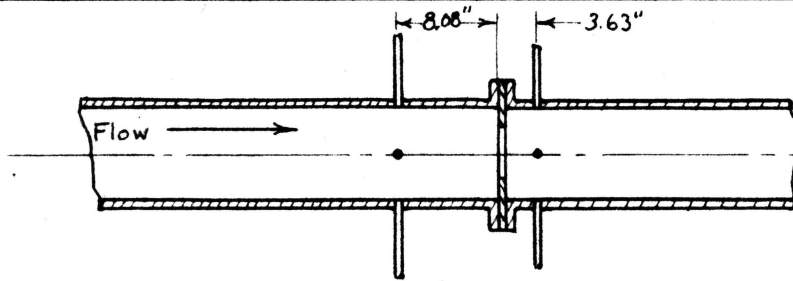


Figure 4. Orifice Pipe Taps

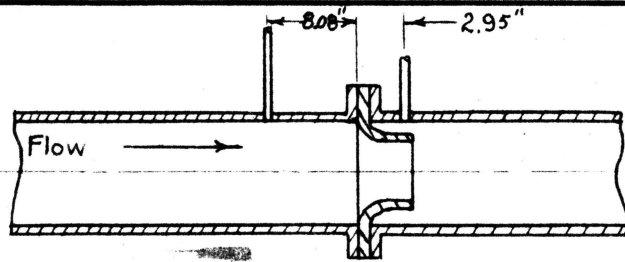


Figure 5. Nozzle with Pipe Taps

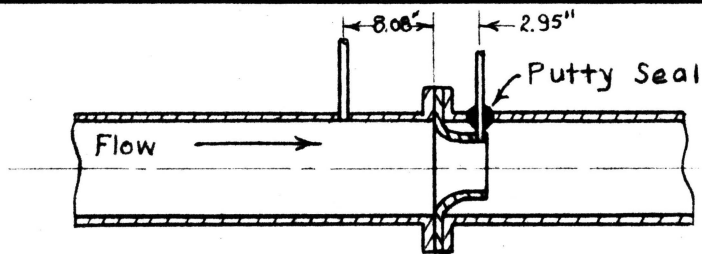


Figure 6. Nozzle with Throat Taps

Apparatus and Materials Used

The coal flowmeter was set up in the pipe that formed the apparatus that is illustrated in Figure 13. The major parts of the apparatus are as follows.

- I. (a) A centrifugal blower, capable of delivering 2000 cubic feet per minute of air, was used to force the air and flyash through the meter.

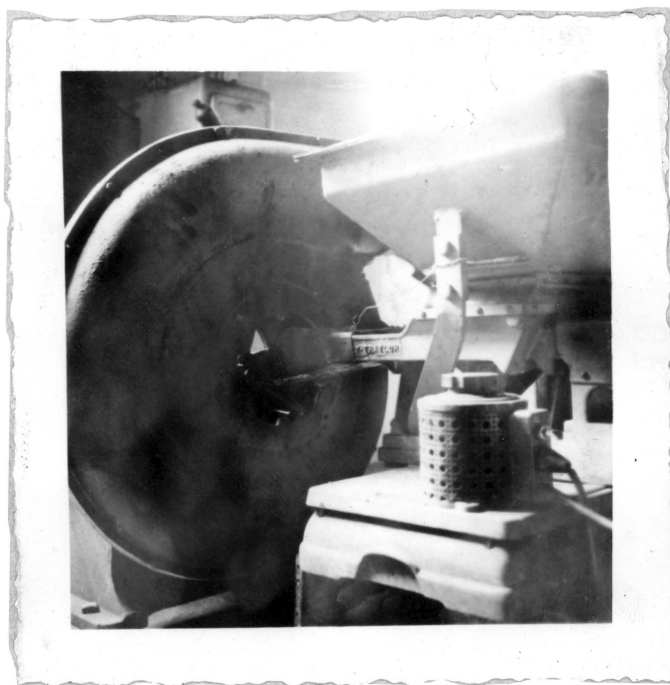


Fig. 7. The Blower, Feeder, and Feeder Control

- (b) A five horsepower, 230 volt direct current, compound wound electric motor was used to drive the blower rotor.
- (c) A six-inch controlled variable feed Jefferies coal feeder was used to introduce the flyash into the air stream at the desired rate of feed. This feeder was of the electric vibrating type and operated on 110 volt AC current.

- (d) A Fairbanks Morse platform scale (range 0-120 lbs) was used to weigh the flyash.



Fig. 8. The Blower, Feeder, Feeder Control, and Scale

- (e) A stop watch was used to time each test run.
- (f) A tachometer was used to determine the blower speed.
- (g) A multiple tube air straightener was placed in the line immediately following the blower.
- (h) The main pipe section of the apparatus was 8 inch diameter heavy cast iron pipe.
- (i) The orifice and nozzle were made from steel according to the drawings and design that appear in the previous section of this thesis.

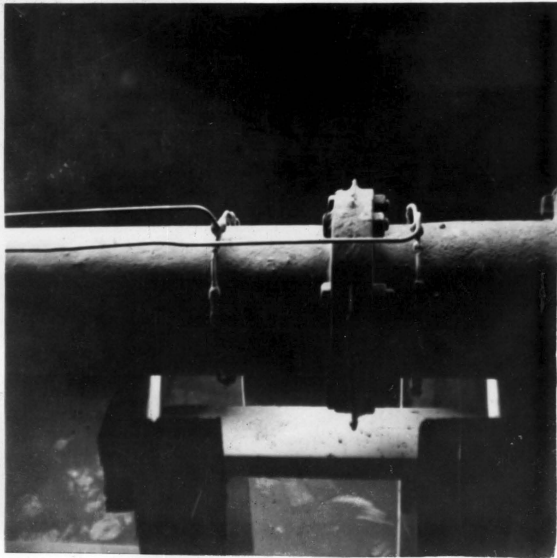


Fig. 9. Orifice



Fig. 10. Nozzle

(j) The static head pressure, nozzle differential pressure, and the orifice differential pressure were measured by three water filled U-tube manometers.

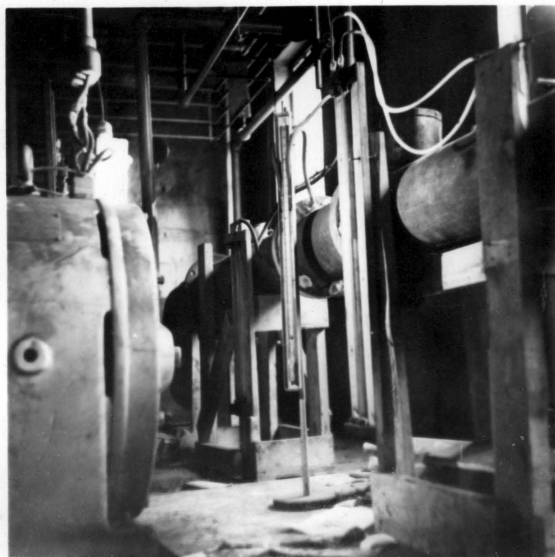


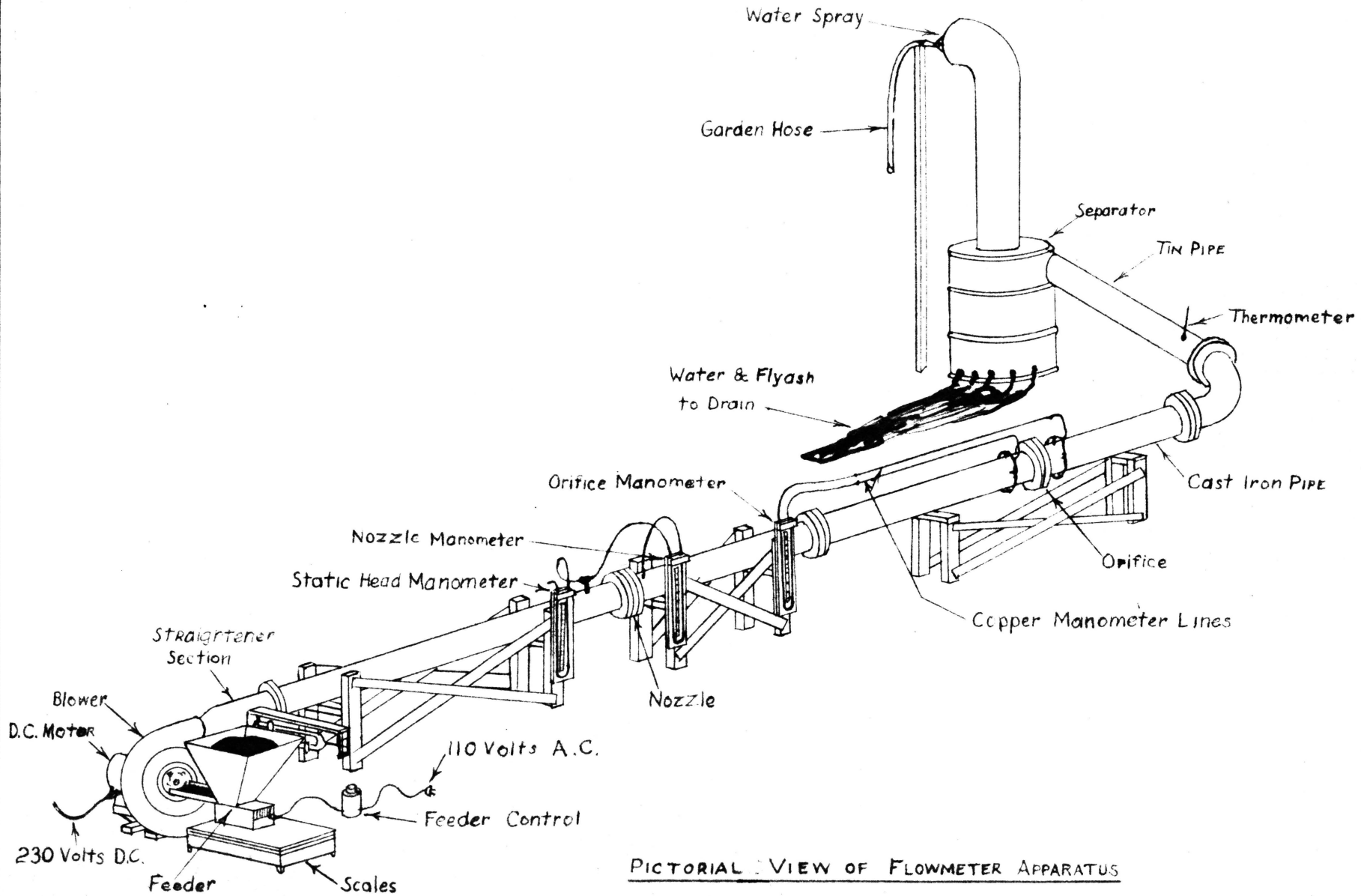
Fig. 11. The Flowmeter Showing The Manometers

- (k) A thermometer (range 0-120° F.) was placed in a thermometer well for the purpose of finding the air flyash mixture temperature.
- (l) A eight-inch diameter length of tin pipe was used to carry the mixture out of the building to the separator.
- (m) A separator was used to separate the flyash from the air after the mixture had passed through the meter. The separator was constructed by cutting a hole in the top and side of a 55 gallon oil drum. The pipe carrying the flyash air mixture to the separator was placed in the oil drum at the side hole and at a tangent to the circle formed by passing a horizontal plane through the drum. A 12-inch diameter tin pipe was inserted through the hole in the top of the drum. The lower end of this pipe extended to within one foot of the bottom of the drum. A garden hose was set such that a water spray was played down the exit pipe from the separator. A number of small holes were punched in the bottom of the oil drum. When the flyash was being forced through the apparatus, the water spray removed most of the flyash and carried it to the bottom of the drum, where the water flyash mixture passed out the punched holes and then passed down the drain.



Fig. 12.
The Separator

- (n) A source of direct current was obtained from the motor-generator set located in the Mechanical Laboratory.
 - (o) The Barometer in the Mechanical Laboratory was used for all Barometer readings.
 - (p) The flyash used to test the flowmeter was obtained from the Virginian Railway Power Plant at Narrows, Virginia. Sieve analysis showed that the flyash used passed an average of 53 per cent through a 200 mesh sieve.
- II. (a) For sieving the flyash samples, a Tyler eight-inch Rotap screening machine was used. A 200 mesh sieve was used.
- (b) For the sieve analysis, a two-range Toledo Scale was used. The two ranges were 0-50 grams and 0-10 Kilograms.



PICTORIAL VIEW OF FLOWMETER APPARATUS

FIGURE 13

Method of Procedure

The plan of the investigation was to determine the rate of flyash flow in pounds per hour through the pipe line. The motor-generator set was started after which the blower motor was started and brought up to speed. A clean air test was first run, orifice and nozzle readings were taken to check the design coefficients against the actual coefficients of operations. The coal feeder was filled and the weight of the coal feeder plus the weight of the flyash were recorded. The feeder control was set to the desired rate of feed.

A 100-gram sample of the flyash was taken before each run was started for a sieve analysis of the flyash. At the beginning of the run the coal feed and the stop watch were started simultaneously. Two observers took static head, nozzle differential, and orifice differential manometer readings continually during the duration of the run. In this way each manometer was read on an average of ten times for the one minute run. During the run, a third observer recorded the barometric pressure, and the temperature of the mixture within the pipe. A fourth person recorded the weight of flyash used for each run, the time for each run, and operated the flyash feeder. At the conclusion of each run the weight of the feeder and remaining flyash were recorded. The water spray on the exit of the separator was kept running for the duration of the tests. The speed of the blower was checked before, during and after each run with a tachometer and it remained constant. The

feed rate of the flyash was adjusted after each run to give a different air-fuel ratio on the following run.

The first set of tests consisting of eleven runs were made with pipe taps installed on the nozzle manometer connections. The next two sets of tests consisting of thirty runs were made with throat taps installed on the nozzle manometer connections. The procedure for the different sets of tests were identical. The total number of runs in the combined set of tests were forty-one.

Table 1

Set A - Nozzle with Pipe Taps

Run Number	Time Sec.	Barometric Pressure in. Hg.	Temperature °F	Static Pressure Before Run in. H ₂ O	Static Pressure During Run in. H ₂ O	Orifice Differential Average in. H ₂ O	Nozzle Differential Average in. H ₂ O
1	60	27.94	81	5.85	5.85	4.14	2.45
2	60	27.94	78	5.85	5.85	3.69	2.37
3	40.6	27.94	77	5.85	5.85	3.90	2.86
4	60.02	27.94	79	5.85	5.85	3.73	2.77
5	50.8	27.94	79	5.85	5.85	3.48	2.45
6	30	27.94	78	5.85	5.85	2.26	1.95
7	30	27.94	77	5.85	5.85	2.61	2.00
8	60	27.94	78	5.85	5.85	3.78	2.14
9	60	27.94	78	5.85	5.85	3.40	2.2
10	54.1	27.94	78	5.85	5.85	3.25	2.23
11	60	27.94	77	5.85	5.85	3.65	2.51
12	60	27.94	78	5.85	5.85	3.96	2.55
13	60.2	27.94	77	5.85	5.85	3.84	2.54

Table 2

Set B - Nozzle with Throat Taps

Run Number	Time Sec.	Barometric Pressure in. Hg.	Temperature °F	Static Pressure Before Run in. H ₂ O	Static Pressure During Run in. H ₂ O	Orifice Differential Average in. H ₂ O	Nozzle Differential Average in. H ₂ O
1	60	28.08	79.5	6.9	6.9	4.15	2.83
2	60	28.08	78.5	6.9	6.88	3.50	2.87
3	60	28.08	78	6.9	6.9	3.51	2.91
4	59.9	28.08	78	6.9	6.9	3.29	2.88
5	60	28.08	78	6.9	6.85	3.3	2.84
6	60	28.08	78	7.0	6.72	3.1	2.75
7	60	28.08	77.5	6.8	6.80	2.97	2.71
8	60	28.08	78	6.95	6.81	2.9	2.57
9	60	28.08	78	7.0	6.61	2.75	2.33
10	60	28.08	77.5	6.95	6.31	2.35	2.20
11	42.4	28.08	77.5	6.9	5.1	1.96	1.58
12	52.3	28.08	78	6.3	5.17	3.25	2.67
13	43.4	28.10	78	6.4	6.20	3.70	3.2
14	60	28.10	78	6.55	6.40	3.93	3.20
15	60	28.10	77.5	6.55	6.5	4.0	3.24
16	60	28.10	77.5	6.6	6.6	4.20	3.35
17	49.8	28.10	77.5	6.65	6.39	3.65	3.12

Table 3

Set C - Nozzle with Throat Taps

Run Number	Time Sec.	Barometric Pressure in. Hg.	Temperature °F	Static Pressure Before Run in. H ₂ O	Static Pressure During Run in. H ₂ O	Orifice Differential Average in. H ₂ O	Nozzle Differential Average in. H ₂ O
1	49.2	27.99	78	6.2	6.2	4.0	3.20
2	52.8	27.99	79	6.2	6.2	3.16	2.94
3	60	27.99	79	6.2	6.2	4.1	3.22
4	60	27.99	79	6.2	6.2	3.79	3.17
5	60	27.99	78	6.2	6.2	3.54	3.02
6	60	27.99	78	6.2	6.2	3.19	2.88
7	60	27.97	78	6.2	6.2	3.20	2.86
8	60	27.97	78	6.2	6.2	3.15	2.75
9	60.01	27.97	78	6.2	6.2	3.31	2.79
10	60	27.97	78	6.2	6.2	2.74	2.50
11	40.5	27.97	78	6.2	6.2	2.16	1.97

Table 4

Set A - Nozzle with Pipe Taps

Run Number	Air Flow Before Run #/Hr	Air Fuel Ratio	Indicated Air Flow #/Hr	Indicated Coal Flow #/Hr	Corrected Indicated Coal Flow #/Hr	Actual Coal Flow #/Hr	Per Cent Error
1	4470	16	4315	205	-	270	-
2	4375	7.46	4085	585	488	548	-10.95
3	4247	4.36	4270	1120	1230	978	+25.60
4	4275	3.00	4110	1290	1635	1368	+19.50
5	4525	2.00	3960	1005	1975	1985	- .60
6	4290	1.31	3250	1460	2690	2520	+ 6.75
7	4075	1.44	3440	1235	2490	2385	+ 4.40
8	4247	12.65	4135	-	-	326	-
9	4290	6.58	3920	575	513	596	-13.80
10	4247	4.41	3830	840	918	868	+ 5.76
11	4400	5.84	4070	860	823	698	+17.90
12	4360	10.75	4240	572	387	394	- 1.80
13	4400	7.44	4210	590	494	566	-12.38

Table 5

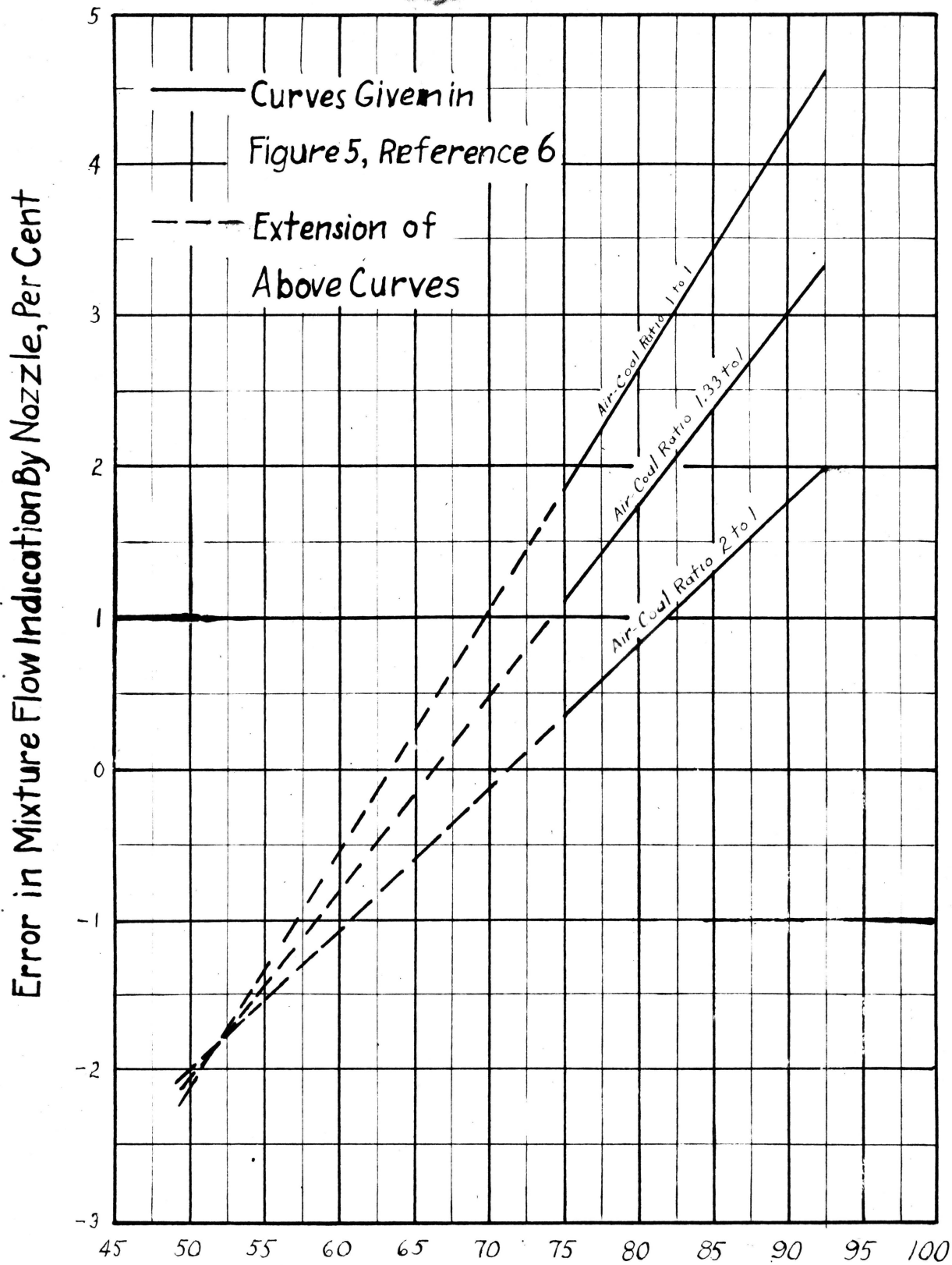
Set B - Nozzle with Throat Taps

Run Number	Air Flow Before Run #/Hr	Air Fuel Ratio	Indicated Air Flow #/Hr	Indicated Coal Flow #/Hr	Corrected Indicated Coal Flow #/Hr	Actual Coal Flow #/Hr	Per Cent Error
1	4370	23.00	4340	-	-	188	-
2	4370	7.37	3980	520	435	540	-17.60
3	4230	7.64	3990	570	471	521	-19.00
4	4370	5.44	3865	793	793	710	+11.70
5	4075	6.00	3875	745	706	646	+9.30
6	4000	3.86	3750	835	983	971	+1.24
7	4050	4.18	3670	970	1100	878	+25.30
8	4020	3.84	3630	800	941	945	- .40
9	4020	2.96	3531	584	764	1192	-35.90
10	3825	2.54	3270	950	1300	1290	+ .09
11	3725	1.60	3670	-	-	2300	-
12	4525	2.15	3840	490	1620	1780	- 9.00
13	4400	3.92	4100	780	907	1046	-13.28
14	4430	6.74	4170	630	558	619	- 9.86
15	4430	8.12	4260	495	378	525	-28.00
16	4430	13.80	4365	405	-	319	-
17	4525	3.78	4060	750	889	1075	-17.30

Table 6

Set C - Nozzle Pipe Taps

Run Number	Air Flow Before Run #/Hr	Air Fuel Ratio	Indicated Air Flow #/Hr	Indicated Coal Flow #/Hr	Corrected Indicated Coal Flow #/Hr	Actual Coal Flow #/Hr	Per Cent Error
1	4400	7.88	4250	400	324	540	-40.00
2	4430	2.30	3885	815	1700	1685	- .90
3	4350	10.50	4210	540	370	401	- 7.73
4	4430	7.80	4135	630	510	529	- 3.60
5	4270	5.74	4000	700	667	697	- 4.30
6	4100	3.07	3800	920	1180	1238	- 4.70
7	4170	3.83	3805	875	1030	993	✓ 3.80
8	4140	4.38	3775	755	834	861	- 3.14
9	4270	5.68	3870	630	643	682	- 5.72
10	3780	4.00	3580	890	1022	885	✓ 15.50
11	3820	1.32	3130	800	1880	2370	-20.70



Particle Fineness, Per Cent Through 200 Mesh

FIGURE 14 EFFECT OF PARTICLE SIZE AND AIR-FUEL RATIO ON Air-Coal Flow of Nozzle

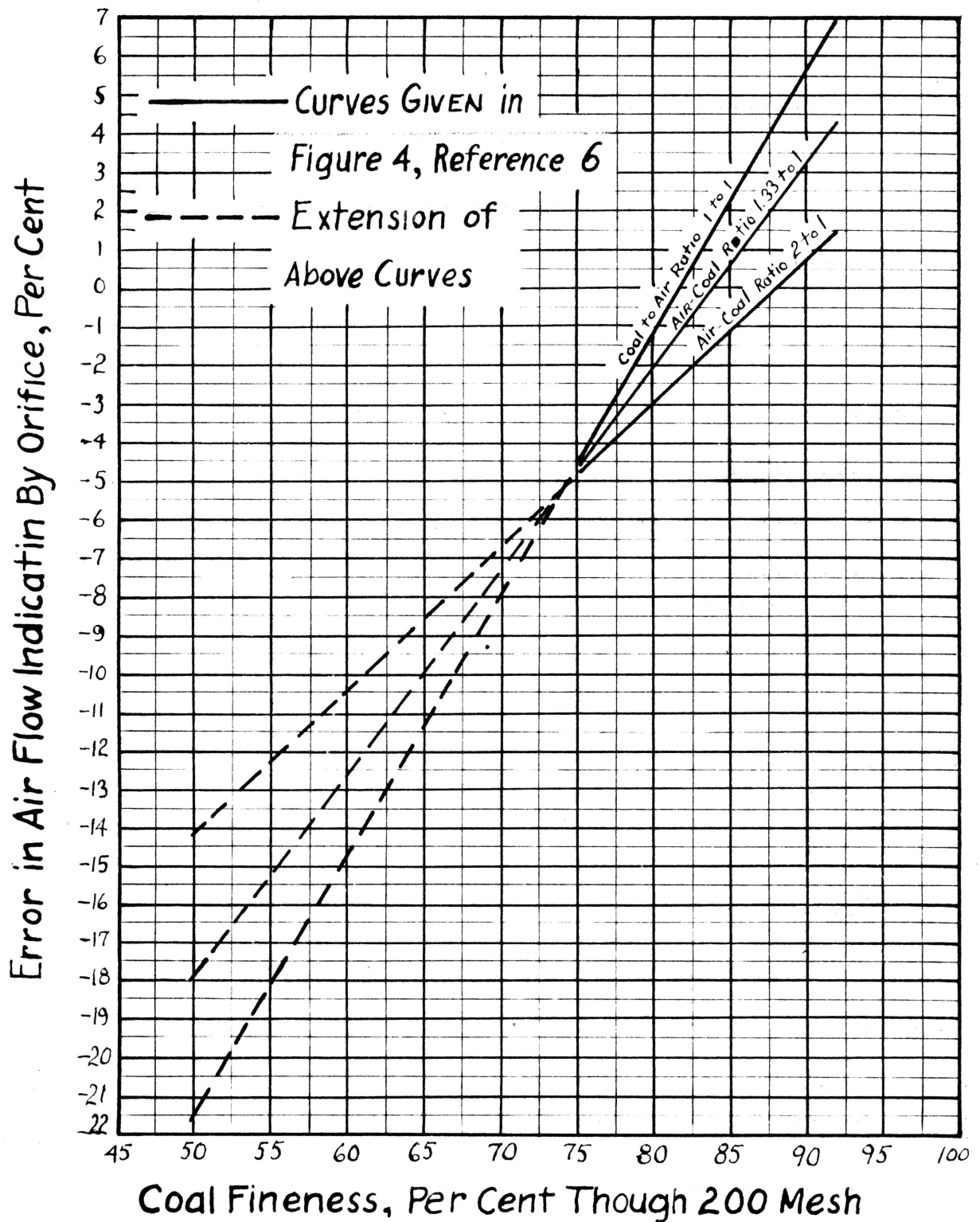
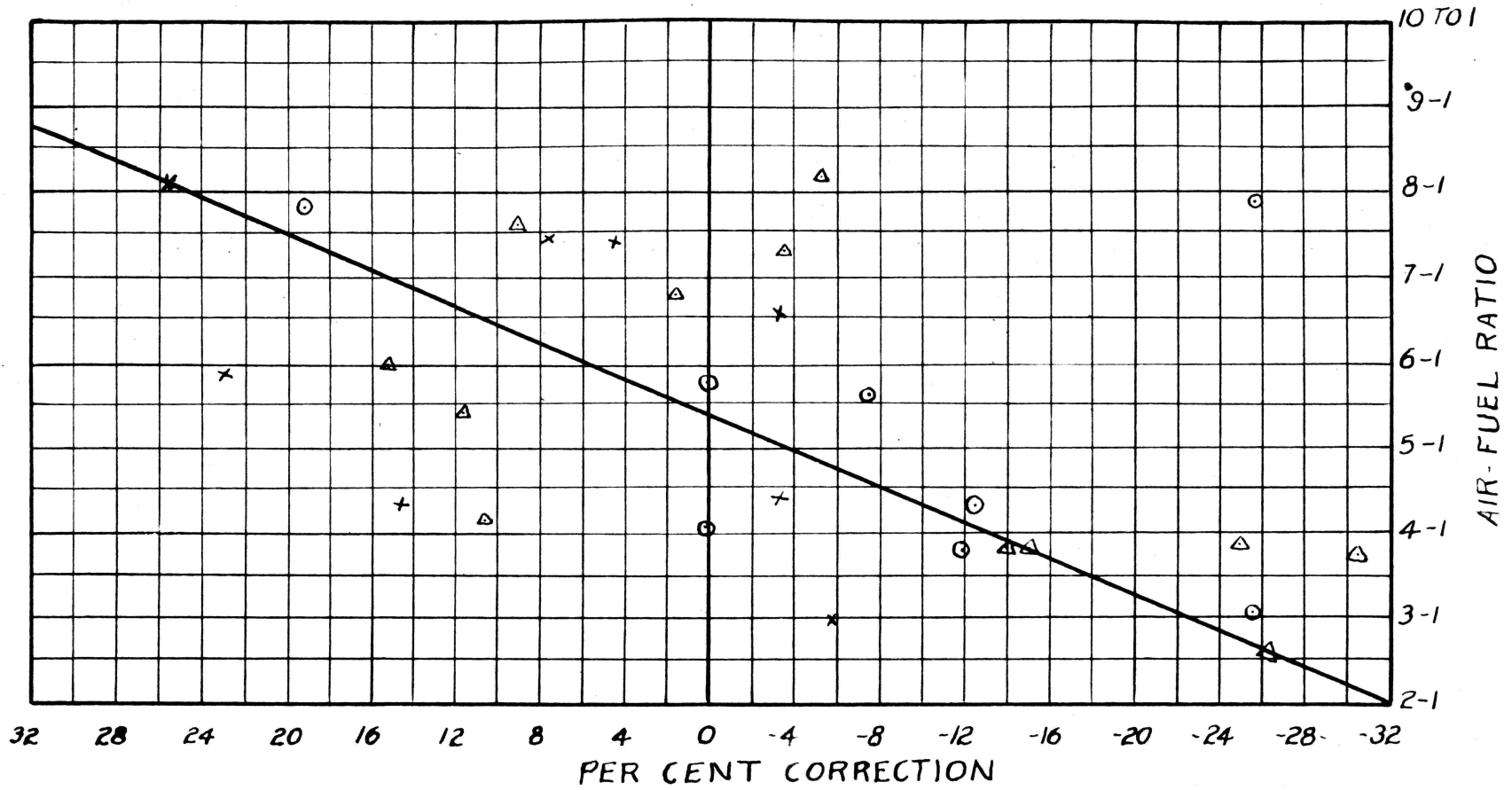


FIGURE 15 EFFECT OF PARTICLE SIZE AND AIR-FUEL RATIO ON
AIR FLOW INDICATION OF ORIFICE



○ SET A
 △ SET B
 × SET C

FIG.16 CORRECTION CURVE FOR INDICATED COAL FLOW

Calculation Used in Determining Flyash Flow

1. Indicated Air flow in pounds per hour as indicated by orifice.

$$W_a = 9250 \sqrt{\frac{1B}{T}}$$

$$W_a = 9250 \sqrt{\frac{3.48 \times 28.442}{537}}$$

$$W_a = 4110 \text{ pounds per hour}$$

W_a = air flow pounds per hour

9250 = constant, previously computed in this thesis

i = average orifice differential, inches of water

B = Barometric pressure at point of test, plus the upstream pressure in the line before the element, inches Hg.

T = Temperature of fluid flowing through element, °R abs.

2. Indicated mixture flow in pounds per hour as indicated by nozzle.

$$W_m = 12310 \sqrt{\frac{1B}{T}}$$

$$W_m = 12310 \sqrt{\frac{2.45 \times 28.442}{537}}$$

$$W_m = 4425 \text{ pounds per hour}$$

W_m = Mixture flow pounds per hour

12310 = Constant previously computed in this thesis.

i = Average nozzle differential, inches of water

B = Barometric pressure at point of test, plus the upstream pressure in the line before the element, in Hg.

T = Temperature of fluid flowing through element, °R Abs.

3. Weight of indicated flyash flow pounds per hour.

$$W_c = \frac{W_m^2}{W_a} - W_a$$

$$W_c = \frac{(4425)^2}{(4110)} - (4110)$$

$$W_c = 1005 \text{ pounds per hour}$$

W_c indicates flyash flow pounds per hour

W_m Mixture flow pounds per hour

W_a Air flow pounds per hour

4. Correction factors.

For air-fuel ratio of 2 to 1 or less correction factors taken from figures 14 and 15.

$$\text{Air-fuel ratio} = 2.00$$

$$\text{Correction factor for orifice} = -13 \text{ per cent}$$

$$\text{Correction factor for nozzle} = -2.5 \text{ per cent}$$

$$\text{Corrected air flow} = 3960 \times (100 - 13)$$

$$\text{Corrected air flow} = 3420$$

$$\text{Corrected mixture flow} = 4425 \times (1.00 - .025)$$

$$\text{Corrected mixture flow} = 4325$$

$$\text{Corrected flyash flow} = \frac{W_m^2}{W_a} - W_a$$

$$= \frac{(4325)^2}{3420} - 3420$$

$$= 1975$$

For air-fuel ratios greater than 2 to 1.

Correction factor taken from figure 16.

$$\text{Air-fuel ratio} = 3.07$$

$$\text{Correction factor} = 22 \text{ per cent}$$

$$\text{Corrected indicated flyash flow} = 920 + (100 - 22)$$

$$\text{Corrected indicated flyash flow} = 1180$$

5. Per cent error.

Per Cent error =

$$100 \left(\frac{\text{Corrected indicated flyash flow} - \text{Actual flyash flow}}{\text{Actual flyash flow}} \right)$$

Per cent error =

$$100 \left(\frac{1975 - 1985}{1985} \right)$$

Per cent error =

-.6 per cent

DISCUSSION

As has been stated in the object of this thesis, it was the authors intention to closely simulate actual conditions that exist in a power plant. In two respects the authors failed to do this. First, flyash was used instead of coal. The authors pulverized approximately 1000 pounds of bituminous coal in a small ball mill located in the Mining Laboratory. Although this operation required about 40 hours, the resulting pulverized coal would only pass about 30 per cent through a 200 mesh screen. Although this is not as fine as the pulverized coal used in actual practice, the authors decided to use this coal to test the meter. During preliminary tests on the meter when pulverized coal was being used and while feeding and blowing the coal through the meter, the resulting dust that was stirred up became excessive. A thick haze of coal dust filled the entire room in which the tests were being made. The authors felt that this created a serious explosive hazard and felt that it was inadvisable to continue using coal for the tests. Therefore, flyash was substituted for the coal. The flyash was of a finer particle size than the pulverized coal that was to have been used. Sieve analysis showed that the flyash passed approximately 54 per cent through a 200 per cent mesh sieve. The particle size was the second shortcoming of the authors intentions. From the three questionnaires sent to the three power plants it can be seen the particle size of the coal

used at those three plants varied from 79 per cent to 90 per cent through a 200 mesh sieve. Fifty per cent through 200 mesh is considerably below this range.

With the exception of the above, actual power plant conditions were approximated. The pipe line was a relative large one. The velocity and static pressure in the pipe line are within the range found in actual power plant practice. The pipe line and meter could be a typical pipe line leading to a burner in a typical boiler furnace. If this typical furnace had eight burners with a flowmeter installed in each line, the total power consumption required to overcome the power loss through the flowmeters would be 9.080 hp. At full load this boiler would consume approximately 36,000 pounds of coal per hour. This would give a boiler capacity of around 375,000 pounds of steam per hour.

Another difficulty that was encountered during the construction of the apparatus was the method of feeding the fly-ash into the air stream. It was the original intention of the authors to introduce the flyash through a slot in the top of the pipe. The slot was constructed such that the air velocity in the pipe would cause a suction down through the slot. The feeder could therefore be placed over this slot and the fly-ash could be funneled down through to the air stream. When the pipe sections were being set up, a strong suction was evident through the slot when the blower was operated. After the two

flow elements had been placed in position and the separator placed at the end of the test pipe, a back pressure was built up in the pipe when the blower was operated. This caused air to be forced out of the slot and made it impossible to feed flyash through the slot. The authors then decided to feed the flyash directly into the blower suction. Therefore the feeder was set in place on a platform such that the feeder chute fed the flyash directly into the blower.

Feeding the flyash through the suction side of the blower brought up an unexpected problem. The flow of air through the pipe line was slowed down considerably when the flyash was fed into the air stream. Since it was impossible to install an orifice before the introduction of flyash into the pipe line, the authors decided to use the orifice differential as indicated to compute the flow of air in the line. The slowing down of the air stream was believed to be caused by the following: blocking of the suction side of the fan due to the introduction of the flyash and the additional energy needed to convey the flyash through the pipe line. The RPM of the blower was taken before, after and during the runs and it remained relatively constant.

After using pipe taps on the nozzle for the first set of tests consisting of 11 runs, the taps were drilled for the placing of throat taps in the nozzle. It was necessary to compute a new coefficient of flow under these new conditions. The accuracy of the flowmeter remained unchanged.

On the completion of the test the equipment was dis-

mantled and the nozzle and orifice were inspected for possible wear and erosion. Around the face of the sharp edge opening of the orifice a hard crust of flyash had formed and a slight erosion had taken place. This was also indicative of the curve surface from the face to the throat section of the nozzle.

A problem encountered by previous investigators was that of coal plugging the manometer lines. This was caused by leaks in the line. No trouble of this type was experienced by the authors.

The results of this series of test are not within the accuracy limits of the test conducted by Messrs. Carlson, Frazier, and Engdahl on their investigation. It is the belief of the authors, that to obtain accuracy within their limits of plus or minus five per cent it would be necessary to make longer runs, thus getting a better overall average of readings taken during the runs. Since a very slight error obtained in the nozzle or orifice differential, when placed in the meter equation magnifies the error considerably. It is also obvious that a slight error in the weight of flyash introduced into the line, when multiplied by sixty will induce an appreciable error.

Correction factors shown in figures 14 and 15 were used to correct the indicated nozzle and orifice flows on air-fuel ratios of 2 to 1 or less. These curves were taken from the paper presented by Messrs. Carlson, Frazier and Engdahl. The highest air-fuel ratios shown on these curves were 2 to 1, so the authors plotted correction curves of a different nature to be applied to the indicated flyash flow on air-fuel ratios

above 2 to 1. This curve was drawn by plotting the per cent error the indicated flyash flow differed from the actual flow of flyash in pounds per hour versus the air-fuel ratio.

Approximately 50 per cent of the results obtained fall within plus or minus 10 per cent of the actual flyash flow. Approximately 75 per cent of the results obtained fall within plus or minus 20 per cent of the actual flyash flow. The remaining 25 per cent of the results are within 40 per cent of the actual flow. The average results, are within plus 12.45 per cent or minus 10.62 per cent of the actual flyash flow. The results, while not as accurate as desired, are considered good by the authors under the test conditions.

CONCLUSIONS

1. Pipe size has no apparent effect on the accuracy of the flowmeter.
2. The selection of pipe or throat taps for the nozzle manometer connections has no effect on the indicated results of meter.
3. The flow of particle sizes of the flyash of 50 per cent through 200 mesh sieve can be accurately measured with this meter with the proper correction factor.
4. The nozzle and orifice should be made of a very hard material that is resistant to erosion over an extended period of use.
5. The results can be reproduced from day to day without any special conditions prevailing.

RECOMMENDATIONS

1. An additional orifice should be placed in the pipe line before the introduction of the flyash into the pipe line for the measurement of the exact air flow. This would require a longer section of pipe.
2. A screw type feeder should be employed to convey the flyash from a pressurized tank to the pipe line.
3. A dust collector should be obtained from a manufacture of dust collectors, so that the flyash might be used again for additional runs.
4. Longer test runs should be made to obtain greater accuracy of results.

APPENDICES

Bibliography

1. Bethel, Atwater, Smith, and Stackman. "Industrial Organization and Management." The McGraw-Hill Book Company, New York, 1945, page 289.
2. Hudson, W. G. "Weighing Coal in the Power Plant." Power Plant Engineering, September 1947, page 101.
3. Fealo, S. N. and Drieg, E., "The Tidd Plant of the Ohio Power Company." Power Plant Engineering, March 1947.
4. Sporn, P., "The 2000 psi, 1050⁰ F. and 1000⁰ F. Reheat Cycle at the Philip Sporn and Twin Branch Steam Electric Station." Transactions of the ASME, May 1948, Vol. 70, No. 4, page 387.
5. Allardice, T. B., "Open-Pass, 2,500 Pound Natural Circulation Boiler." Electric World, Vol. 116, October 18, 1941, page 87.
6. Carlson, H. W., Frazier, P. M., and Engdahl, P. B., "A Meter for Flowing Mixtures of Air and Pulverized Coal." Transactions of the ASME, Vol. 70, No. 2, February 1948.
7. Pouse, H. "Fluid Mechanics for Hydraulic Engineers." The McGraw-Hill Book Company, New York, 1938, page 262.
8. Engdahl, R. B., letter to the authors, Messrs. Giddings and Speegle, at the Virginia Polytechnic Institute, December 1948.

9. Barnard, Ellenwood, Hirshfeld, "Heat-Power Engineering, Part II." John Wiley and Sons, Inc. New York, page 515, figure 594.
10. Anonymous, "Information on Instruments and Apparatus, Part 5 Measurement of Quantity of Materials, Chapter 4, Flow Measurement by Means of Standard Nozzles and Orifice Plates" ASME Power Test Codes, 1940.
11. de Lorenzi, Otto, "Combustion Engineering." Combustion Engineering Company, Inc. New York, 1948.
12. Leisman, Marcel A., "An Analysis of Mechanical Methods of Dust Collection." Chemical Metallurgical Engineer, October, 1930, Vol. 37, No.10, page 630.
13. Drinker, Phillip and Hatch, Theodore, "Industrial Dust" The McGraw-Hill Book Company, Inc. New York, 1936.
14. Rowley, L. M. Mc Cabe, I.C., and Skrozki, B., "Fuels and Firing." Power, December, 1948.
15. Kent, R. T., "Kent's Mechanical Engineers' Handbook" Power Eleventh Edition, John Wiley and Sons, New York, 1948.
16. Marks, L. S., "Mechanical Engineers' Handbook.", Fourth Edition, McGraw-Hill Book Company, Inc. New York, 1947.
17. Moore, F. T., "Power Plant Engineering and Design", second Edition. D. Van Nostrand Company, New York, 1942.
18. Gaffert, G. A., "Steam Power Stations.", Third Edition, McGraw-Hill Book Company, Inc. New York, 1946.

Calculations to Check the Calibration of the Meter

From the design of the meter, it can be seen that the two equations used to find the flow by the nozzle and the orifice are $W_n = 12310 \sqrt{\frac{1B}{T}}$ and $W_o = 9250 \sqrt{\frac{1B}{T}}$. A series of clean air runs were made to calibrate the orifice against the nozzle. The authors believed the nozzle to be the most accurate flow element of the two. Therefore, the motor and blower were operated at different speeds and the flow of air was calculated by the nozzle and the orifice for each clean air run.

The flow of the nozzle and orifice compared as follows:

Nozzle with Pipe Taps

1. Nozzle differential = 1.51 inches of water

Orifice differential = 2.7 inches of water

$$W_o = 9250 \sqrt{\frac{1B}{T}}$$

Where 1 = differential across element, inches of water.

B = Barometer pressure plus static pressure in the pipe, inches of Mercury.

T = Absolute temperature.

$$W_o = 9250 \sqrt{\frac{2.7 \times 28.239}{549}}$$

$W_o = 3444.62$ pounds of air per hour.

$$W_n = 12310 \sqrt{\frac{1.51 \times 28.239}{549}}$$

$W_n = 3431.79$ pounds of air per hour

For this run the orifice had a \neq 0.376 per cent error.

2. Nozzle Differential = 1.75 inches of water. Orifice differential = 3.15 inches of water.

$$W_o = 9250 \sqrt{\frac{3.15(28.239)}{549}}$$

$W_o = 3705.31$ pounds of air per hour

$$W_n = 12310 \sqrt{\frac{1.75(28.239)}{549}}$$

$W_n = 3718.65$ pounds of air per hour

For this run the orifice had a = -0.36 per cent error.

3. Nozzle differential = 2.06 inches of water. Orifice differential = 3.62 inches of water.

$$W_o = 9250 \sqrt{\frac{3.62 \times 28.338}{550}}$$

$W_o = 3997.75$ pounds of air per hour

$$W_n = 12310 \sqrt{\frac{2.064(28.338)}{550}}$$

$W_n = 4004.905$

For this run the orifice had a - 0.1785 per cent error.

The orifice error was so small that it was decided not to adjust the orifice coefficient.

The Power Test Code specified pipe taps with the nozzle. When throat taps were installed, the nozzle gave a different clean-air flow indication as compared with the orifice. Therefore the orifice was chosen as a standard and the nozzle coefficient was adjusted to give the same flow indication as the orifice.

$$W_o = 9250 \sqrt{\frac{18}{5}}$$

$$W_o = 9250 \sqrt{\frac{4.0 \times 28.58}{538}}$$

$W_o = 4265$ pounds per hour

Equating the flow of air by the orifice against the flow indicated by the nozzle.

$$W_o = W_n = C \sqrt{\frac{1B}{T}}$$
$$4265 = C \sqrt{\frac{2.91 \times 28.58}{538}}$$

$$C = 10,850$$

$$C = 413.3 \times K \times D^2$$

$$413.3 = \text{Constant}$$

K = Flow coefficient

D = Diameter of Throat Section of Nozzle

$$K = \frac{10,850}{413.3 \times (5.25)^2}$$

$$K = .956$$

K = Flow Coefficient