INSTANTANEOUS INDIVIDUAL FLOW RATE MEASUREMENT IN A COAL - AIR SYSTEM

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By

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ABSTRACT

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This research effort is the initial step in the development of an integrated control system capable of continuously maintaining a pulverized fuel energy conversion system in an optimal economic operating configuration. Attention was directed towards the development of an accurate mass flow meter for instantaneous individual flow rate measurement in a pulverized coal-air system.

The isokinetic two-phase sampling tube developed was used to measure both coal and air flow rate at points within the twelve inch fuel lines of the Michigan State University Power Plant. Velocity profiles were obtained and are graphically presented.

In general, the flow measurement technique used proved to be very good for determining velocity profiles. No suitable alternate method for measuring the profiles in these large conduits was found in a search of the literature on fluidization, two-phase flow, and power plant design and operation.

It is anticipated that this isokinetic sampling method can be used to calibrate continuous flow measurement devices to be developed in subsequent portions of this control project.

ACKNOWLEDGMENT

The author wishes to dedicate this thesis to his parents. Of all his counselors, they have been the most helpful.

Location of the University Power Plant and the assistance of Mr. Jesse Campbell and Mr. Wayne Yates made it possible to conduct this research at a full-scale plant. Organizational and clerical needs for this project were ably accomplished by the staff of the Division of Engineering Research, Michigan State University. The Shop Services Supervisor, Mr. Donald Childs, offered valuable suggestions and assistance in the fabrication of equipment. The author is also grateful to the Detroit Edison Company for providing financial support for this research and for the author during the summer of 1967. Especially valuable guidance was supplied by Dr. George Coulman during this research and the author wishes to express his sincere appreciation to him.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

This research effort is the initial step in the development of an integrated control system capable of continuously maintaining a pulverized fuel energy conversion system in an optimal economic operating configuration.

1.1 Total Project

The Detroit Edison Company is sponsoring this research on pulverized coal power plants to gain a more fundamental understanding of the dynamics of the fuel supply and combustion system. It is anticipated that this understanding will lead to a functional control system for the integrated power plant.

A pulverized coal power plant operated by Michigan State University is being used for early work on this project. The plant, completed in 1965, consists of two 250,000 lb. per hour boilers and has an electrical generating capacity of 25,000 kw. The project consists of four related efforts: (1) development and evaluation of pulverized fuel and air flow rate monitoring techniques, (2) determination and monitoring of on-line fuel energy value parameters, (3) study of process dynamics and kinetics of the energy conversion operation, and (4) development of dynamic optimizing control algorithm.

1.2 Study To Date

The initial effort in this control system project was directed towards obtaining precise mass flow measurements of the coal-air stream, although limited studies were conducted on fuel energy value and process dynamics. Flow measurements were considered most important since a wide search of the literature on fluidization, two-phase flow, and power plant design and operation yielded incomplete theoretical and little practical information.

In essence there are three stream properties that must be measured to determine continuously individual flow rates in a solid-gas flow system. These are total flow rate, stream temperature, and effective stream density. However, with such a metering system, accurate calibration is essential to determine the flow rates on an absolute basis.

For this reason the development of an accurate calibration device was attempted first. It was decided to construct an isokinetic two-phase sampling tube that could also be used as a circular pitot tube (Figures 3 and 7). Sampling with this tube it was possible to take point samples of both the solid and air flow rates. Using it as a pitot tube gave an indication of combined flow rates.

These capabilities were utilized to determine flow distribution in a vertical section of the fuel supply line for both the coal and air. From this distribution a relationship was obtained between air and coal flow rates (section 5).

The boiler output (pounds steam/hour) was also correlated with pressure drop across the fuel supply line and a series of point measurements with the sample tube.

A study was also made to determine response times of the boiler and associated equipment.

1.3 Flow Monitoring

Since continuous monitoring is necessary in a control system, total flow rate, stream temperature, and effective stream density will be measured with standard instrumentation that can be calibrated with the aforementioned sample tube.

A venturi meter could be used to determine the total flow rate since solution of the mechanical energy balance will lead to an equation of the form:

$$V_M = C\left(\frac{\Delta P}{\rho_M}\right)^{\frac{1}{2}}$$

where

V_M = total mass flow rate

C = constant

ΔP = pressure drop

ρ_M = effective density of solid-gas mixture.

However, the Michigan State University power plant system lacks the room to insert a venturi in the pulverized coal feed line. The line runs from the pulverizer to a riffle (device to split stream) to the burner. In this line (Figures 1 and 4) there is a pressure drop of about 8 inches of water. It is possible to use the pulverized coal feed line itself as a differential pressure meter, since the solution of the mechanical energy balance for the fuel line will lead to the same equation form as the venturi.

Stream temperature is easily measured by a thermocouple inserted into the fuel line.

A radiation density meter, see Appendix B, would be used to calculate the effective density of the pulverized coal stream without inserting an obstruction into the line and disrupting the flow pattern.

Using the principle of conservation of mass one may write:

$$\rho_M = \frac{\rho_p}{C_p} + \frac{\rho_g}{C_g} \qquad \text{and} \qquad V_M = \frac{V_p}{C_p} + \frac{V_g}{C_g}$$

where

ρ_p = density of particles

ρ_g = density of air

C_p = concentration of particles (lb particles/lb mixture)

C_g = concentration of air (lb air/lb mixture)

V_M = mass velocity mixture

V_p = mass velocity particles

V_g = mass velocity air

T = temperature

Then if Vp is known as a simple function of V_g and ρ_g as a function of T:

$$V_p = f(V_g) \qquad \text{and} \qquad \rho_g = \phi\,(T)$$

One may determine both V_p and V_g as functions of V_M which can be measured as mentioned above

$$V_p = g(V_M) \qquad \text{and} \qquad V_g = h(V_M)$$

The actual relationship between solid particle velocity and gas velocity is shown in Figures 10 and 11.

2. BACKGROUND

2.1 Pneumatic Conveying

Pneumatic conveying of solids has been used for quite some time to transport light, bulky materials, such as raw cotton, woodshavings, and wool. However, within the past decade many new installations incorporating pneumatic transport of pulverized coal, grain, finely divided ore, organic, and inorganic chemicals have been built.

Much information is available on the different types of conveying systems, system selection, equipment, and piping.[14,27] However, a great deal of this material is not connected by theory or precise empirical relationships but rather by "rule-of-thumb" techniques.[20] This is not because of lack of effort or experimental study but because of the exceedingly complex nature of solid-gas flow.

There are several modes of flow possible depending upon the important variables grouped below:[5,39]

1. pipe size, roughness, and orientation;
2. solids density, particle size, shape and size distribution;
3. solids-to-gas weight-rate ratio; and
4. gas velocity.

The solids may be fully suspended and fairly uniformly dispersed over the pipe cross section at one extreme or they may form a layer along the bottom of the tube, only the surface of which moves, at the other extreme. Modes of flow between these two extremes can be easily observed and because of the different paths particles take in each of these modes it is impossible to write one theoretical or empirical equation to describe all modes. Usually the flow is characterized (and specific flow equation chosen) from the ratio of gas velocity to minimum carrying velocity* and from the solids concentration (dense or diffuse flow). The flow equations, however, are generally rough approximations to reality.

Pressure drop is of primary concern to a designer of the aforementioned conveying systems both as a function of the tube or duct system and the flow rate of solid material. For this reason most of the research associated with pneumatic conveying has been directed toward pressure drop determination. Some relationships are commonly used and will be presented later.

Another area where solid-gas flow occurs is fluidized-bed reactor systems. There are several books and papers in this area that deal with the flow of the catalyst (solid) in a gas.[34,39] In a reaction design there is more interest in the time the particle (catalyst) spends

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*Velocity required to convey particles in gas. Theoretically it is the terminal falling velocity, though many particles are too large for Stokes Law (1-100 microns) to be strictly applied.

in the system than there is in a bulk conveying system, hence, interest in the instantaneous solid and gas velocities is greater.

2.2 Pulverized Coal Systems In Power Plants

The firing of pulverized coal has largely developed as an empirical art with theoretical understanding generally following rather than preceding practical accomplishment. The chapter on "Pulverizers" in Combustion Engineering[7] gives an excellent historical background. The initial incentives to burn coal dust were that it was virtually a waste material and by reason of its small size ought to combust very rapidly, whereby permitting a reduction in furnace size. However, in reality general use of pulverized coal and realization of these advantages required development of equipment over many decades.

The "direct firing" system is the simplest of the three commong methods of supplying and firing pulverized coal to a furnace. It consists of crusher, classifier, air supply, and tubes to convey the coal directly to the furnace. Other systems have long or short time storage hoppers and suitable collectors between the crusher and furnace. Hot air or diluted furnace gas supplied to the pulverizer furnishes heat for drying the coal and transports the coal to the furnace. This air is known as primary air and is part of the required combustion air used in the furnace.

In the simplest boiler ductwork system there is a main air duct from the forced draft fan to the air heater and to the burners. In addition, there is a primary air duct from the main hot air duct to the pulverizers. From the point of takeoff of the primary air, the air going to the burners is called secondary air in spite of its large volumetric flow rate. A main gas duct carries the flue gas from the economizer outlet to the air heater to the induced draft fan to the stack. If the furnace is pressurized (an increasingly common practice) and without an induced draft fan, the main gas duct runs directly from the air heater to the stack.

The fineness to which coal should be pulverized depends on many factors. Type of coal is of prime importance. Some coals are of low volatility or swell when exposed to furnace temperatures, while others are quite volatile and ignite and burn readily. Large furnaces may operate on coarser coal than smaller ones simply because of larger furnace volume, length of flame travel and furnace turbulence.

The fineness of pulverized coal is determined by passing the coal through standard sieves (ASTM D 197-30). Since the advent of pulverized coal firing fineness specifications have changed considerably. Initially specifications called for 95 percent minus 100 mesh and 85 percent minus 200 mesh. Now individual systems and coal types dictate a variation in the minus 200 mesh (74 micron) specification from 65 to 85 percent. The minus 100 mesh requirement is largely replaced by specifying that plus 50 mesh (300 micron) material not exceed 2 percent of the total.

It can be seen from the above specifications that it is important to have a large percentage of fine particles, thereby insuring a large surface area, when combusting pulverized coal. However, it is equally important not to have oversized (greater than 50 mesh) particles. As little as 5 percent plus 50 mesh may produce furnace slagging and increased combustion loss (carbon loss) even though combustion conditions are excellent for the finer coal and the total surface area remains unchanged by increasing the minus 200 mesh fraction.

Combustion efficiency is normally affected more by larger size composition, whereas grinding power for the pulverizers is more closely related to the finer size percentages. For these reasons fineness samples are checked periodically in an effort to maintain an acceptable product from the pulverizers with minimum power consumption.

On a direct fired system these samples must come from the fuel line to the furnace. A sampling device, consisting of a sampling nozzle with a hose connecting it to a small cyclone collector and sample jar is used. To get a representative sample the nozzle must traverse the whole pipe diameter in two mutually perpendicular paths, both of which are perpendicular to the axis of the fuel line, at a point where the pipe is as free from bends and other disturbances as possible.

Pulverized coal feeder and fuel piping determine the maximum primary air temperature that can be used in the system. This may be as high as 500°F, although a lower temperature is more common. If 130°F air is used to convey and dry the coal, the relative humidity may be as high as 70 to 90 percent. It is important to maintain the relative humidity of a system below the saturation limit while drying the coal sufficiently to insure good combustion. In direct firing systems higher temperatures may be used since the danger of fires such as may occur in storage bins is less. Common temperatures range from 110° to 200°F depending on the type of coal and moisture content.

The pressure in a pulverized coal conveying system depends upon the system resistance resulting from coal and air flow through the fan, ducts, and the pressure in the furnace as well as the source and temperature of the air. Furnace pressures may range from 8 to 20 inches of water.

As mentioned earlier the velocity required to convey a particle depends partly upon the density of the particle and its size. The density of coal ranges from 50 to 90 lb/ft^3 and the particle size in most systems varies from less than 74 microns to greater than 300 microns. With these wide variations it is difficult to give values of minimum conveying velocity but from practice[10] typical fuel line velocities and densities are:

Density, lb air/lb coal	1.2-2.5	2.5 and over
Velocity if horizontal, ft/sec	80-90	75-80
Velocity if vertical, ft/sec	80-90	45-60

At present the methods of measuring coal flow into a furnace consist entirely of batch methods: usually automatic or manual weighing-dumping equipment incorporated in the fuel handling system. Typical accuracy of the automatic scales is within three to four percent of true total for 10 to 15 dumps. An alternate procedure determines fuel rate from a unit heat balance and fuel heating value. This is generally considered the more accurate method, although good fuel sampling becomes important.

Air flow measurement is usually accomplished through a velocity head type meter, where a constriction in the pipe or duct causes an increase in velocity and a corresponding decrease in static head which may be measured. Orifice plates are probably the most common constriction, although venturi sections are sometimes used if space permits. A pressure differential may also be obtained with an airfoil, which has the following advantages over a venturi section: higher differential pressure with lower permanent loss and shorter length. The airfoil[24] has been tested in an operating power plant and provided good results in a duct 5 feet by 6 feet in cross section.

The differential pressure was found to be more exactly proportional to the square of the flow than with the other differential pressure meters in use. Accuracy of flow measurement by pitot tube techniques are limited because of large velocity profiles in the ducts.

An air flow measurement that is considered superior to the above methods is accomplished by means of an orsat analysis of the flue gas.[7] This method gives an interpretation of only the overall air flow, using CO_2 and O_2 concentrations, and cannot be used for study of air flow distribution within a system.

At present there is no method, that enjoys wide use, for obtaining both coal and air flow rates in a conveying system.

Flow modeling of furnaces and ducts can be successfully used to avoid pitfalls of extrapolation from smaller to larger units. <u>Combustion Engineering</u>[6] devotes a good portion of Chapter 7 to this problem and presents techniques for showing stream lines using either air with smoke or water with solids. These methods might be of help in developing flow meters for coal-air flow.

2.3 Difficulties in Two-Phase Flow Studies

Typical of the difficulties sighted by experimenters in the literature is the following statement by Mehta[26] about solid-gas flow. "Plugging of the pressure taps and tubes to the manometer also prevented accurate measurement of the pressure drop." In plant experience of the Detroit Edison Company and the Michigan State University Power Plant personnel is even more discouraging. All of the experimental work described in the literature dealt with a less hostile environment than that in an operating power plant.

Initial observations by the author showed that even taps as large as ½ inch in diameter became plugged if not cleaned regularly. The coal particles, although small, tend to bridge any openings that do not have a flow through them.

To prevent these difficulties the author's sampling equipment and pressure taps were designed to be purged regularly. Precautions were also taken to purge the sampling tube, cyclone separator, and rotameter section of the coal collecting apparatus. The system was purged before each run and this resulted in two advantages: (1) all openings and taps remained unplugged throughout the entire study, (2) all coal was blown out of the sampling system before each run, thereby accurate coal samples could be taken. It should be noted that the circular pitot-sample tube used was especially designed to operate without plugging (Figures 3 and 7).

Another difficulty that may be encountered in power plant sample taking is agglomeration of the coal in the sample equipment due to the presence of water. The fuel air mixture cools considerably on being removed from the pipe and if the relative humidity is high enough, the gas in the sample tube will be below the dew point, leading to water drop formation. This did not occur in the present study, since the relative humidity in the sample equipment was less than 70%. Insulation on the fuel lines from the pulverizers to the burners, not a common industrial practice, helped prevent this problem at the Michigan State Power Plant.

3. PREVIOUS EXPERIMENTAL INVESTIGATIONS AND THEORY OF SOLID-GAS FLOW

Progress toward understanding the transport of solid particles by gases has been slow and the few quantitative relationships that are available from the literature in this field do not include all relevant variables. These relationships are therefore limited to certain, often undetermined, ranges of the excluded variables. In the following paragraphs only the experiments and relationships most likely to illuminate the problem of pulverized coal measurement are discussed. Hence, dense phase transport is ignored completely and modifications of the flow equations for vertical tubes are not presented. (Dense phase usually indicates a particle concentration greater than 5 lb/ft^3, while the dilute phase is of the order of 0 to 5 lb/ft^3.)

3.1 Velocity Relationships

For a certain gas stream traveling at superficial velocity V, a fixed amount of solid, W, can be carried in dispersed flow. The minimum required gas velocity for this situation is called the saltation velocity. Zenz[39] gives a plot which shows in schematic form the relationship between pressure drop per unit length and V for different constant solids mass rates. It is interesting to note that the lines of constant W are discontinuous at the saltation velocity because solid materials starts to collect on the bottom of the tube, i.e., saltation takes place. Some experimenters have failed to realize that this saltation was taking place during what they thought were steady-state periods.

Both the saltation velocity (for the gas stream) and the critical conveying velocity (for the particles) can be calculated by empirical correlations given by several authors.[27,39] The main use of these velocities is in design, where it is necessary that the flow rates exceed the critical values. Unfortunately, the accuracy of the equations is not great enough to permit their use in other applications.

If the experimental data available on powders of uniform size (i.e., glass balls) is said to be incomplete, the data on mixed particle size powders, such as coal dust, is virtually nonexistent. However, the available information indicates that using techniques such as geometric mean particle size and an additional parameter for degree of size distribution will permit the use of empirical equations based on uniformly sized particles for mixed particle size calculations.

Stockel[34] took a completely theoretical approach to the high speed flow behavior of gas fluidized solids.

He derived equations describing flow in a conduit of changing area, using a simple model restricted to one-dimensional, frictionless, steady flow in the absence of gravity. When he solved the flow equations they gave good approximations to the experimental results he had obtained.

3.2 Friction Loss Relationships

The friction losses in a pneumatic conveying system are also of interest, since they result in a pressure drop. An interesting approach described by Molynux[27] and others[37] relates the friction losses of a gas-solid mixture to that of the gas alone by a factor, B. B is always greater than one and is calculated from graphs of dimensionless variables obtained from experimental data. A typical value of B given for coal dust is 1.16.

Breaking the problem of friction loss down into smaller parts, each perhaps more manageable theoretically, has been the most recent approach to pressure drop calculations. Hinkle, in his Ph.D. thesis at Georgia Institute of Technology, has presented an extensive study of the various factors using data from his experiments in 2- and 3-inch glass pipes. The six forces contributing to pressure drop in dilute conveying are:

(1) The friction of the fluid against the pipe wall.

(2) The force required to move the solids' mass

through the pipe.

(3) In vertical pipes the force required to support the weight of the solids.

(4) The forces required to support and accelerate the fluid.

(5) The forces required to support and accelerate the solid material.

(6) The friction between the pipe and the solids.

Summing these factors Hinkle obtained the following relationship:

$$\Delta P_{\substack{\text{total}\\ \text{horiz.}}} = \frac{V_G^2 \rho_G}{2g} + \frac{WV_p}{g} + \frac{2f\rho_G V_G^2 L}{g D_T}\left(1 + \frac{f_p V_p}{f V_G} \frac{W}{V_G \rho_G}\right)$$

where f = conventional Fanning fluid-to-pipe friction factor;

f_p = fluid-to-solids friction loss in conveying

or

$$f_p = \frac{3\rho_G C_D}{2\rho_p} \frac{D_T}{D_p}\left(\frac{V_G - V_p}{V_p}\right)^2$$

For the above formula to be useful one needs to know the velocity of the particles. From high-speed photography Hinkle determined particle velocity and developed the empirical relationship:

$$\frac{V_p}{V_G} = 1 - 0.179\, D_p^{0.3} \rho_p^{0.5}$$

This represented observed particle velocities to within

$\pm$ 5 percent, but the more common assumption that $v_p = v_g - v_\epsilon$, predicted the particle velocities with no more than $\pm$ 20 percent error. (v_ϵ is a constant representing the lag between gas flow rate and solid flow rate. It may be taken as the saltation velocity.)

Experiments by Mehta[26] showed that particle velocity varied linearly with air velocity for 36-micron particles. (Smaller than Hinkle's 0.014- to 0.33-inch particles.) However, Mehta's 97-micron particles tended to reach a maximum velocity in the range investigated. It is difficult to compare the results of Mehta and Hinkle since the particle diameters differ by two orders of magnitude, but Hinkle actually measured the velocity of individual particles while Mehta used two fast acting gate valves in a section of pipe to "capture" the particles in that section at a given time.

3.3 Solid and Gas Velocity Profiles

Of all the literature the author searched, only the two articles discussed in this section provided an indication of what velocity profiles were to be expected in a two-phase flow system very roughly approximating the power plant fuel line. Other investigations described in the literature used high speed photography, pressure head loss methods, or the "capture technique"* to study two-phase flow. For obvious reasons these techniques do not yield any information on flow profile in a large conduit.

Doig[8] used 300 and 750 micron glass spheres for the solid phase, somewhat larger than pulverized coal. His conduit was 43-mm glass tubing 40 feet long and suspended in a vertical position. He was able to obtain measurements of the air-phase velocity profile with a specially designed cylindrical pitot tube that could be moved across the conduit perpendicular to the flow. Flow velocities were approximately 20 ft/sec (close to choking velocity), but even at this speed conventioned pitot tubes were rapidly damaged by the particles. Doig made no attempt to measure the solid velocity profile; however, he discusses at length the change in air velocity profile due to the presence of the solids. At low average ratios of particle to air concentration the dispersed phase caused the air velocities relative to the single phase profiles to increase in the core and decrease at the wall. At high average concentration ratios there is a decrease in core velocity, tending toward plug flow, while the air velocities increase toward the wall.

Soo[33] studied particle concentration, mass flow

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*This method consists of rapidly closing both ends of a section of the test pipe while flow is taking place. The section is then removed and the amount of solid "captured" is determined.

rate, and solid particle velocity of glass beads (50-micron) and magnesia (35-micron). These are about the same size as the coal dust particles of interest. He used a fiber-optic probe to measure concentration and an electrostatic probe to study flow rate of the solids. The air flow rate was about 130 ft/sec. Conclusions reached were that concentration of solids increases towards the wall of the pipe while the solids' velocity decreases to perhaps 20 percent of the core velocity at the wall. Also the fluid seemed to follow the 1/7 turbulent velocity law while the particle velocity varied nearly linearly with distance from the wall to about the 2/3 power. Soo agrees with Mehta in that the solid velocity varies approximately linearly with the gas velocity. It seems that for this size particles $V_p \approx 1/2\ V_g$.

3.4 Two-Phase Measurement

Most two-phase flow measurements rely on conventional methods, such as Doig's, to determine air flow. However, methods for measuring mass flow rates directly require something different. Most particle flow rates are based on a certain fraction of the particles that interact, proportional to their velocity, with a measuring device. This could consist of electrostatic charge transfer to an electrostatic probe or a condenser, or it might be momentum transfer to a mechanical target. With a stretch of the imagination, one might also include change in inductance of a coil to flow of a material through the core to be in this class. The chief difficulty with these methods or methods that sample the flow is that the particles measured may not be representative of the whole flow.

Lieberman[23] discusses this problem of representative sampling of fine particles. He also discusses the important matter of distortion or modification of the particles or flow during sampling periods. Isokinetic* sampling is very important and Lieberman presents a graph of the relative error that results in nonisokinetic sampling for different ratios of air speed in conduit to air speed in sampling tube. Particle size is a parameter on this graph, but for larger particle sizes the error in particle concentration can be as large as 40%.

Indirect methods for particle flow rate measurement usually consist of some sort of attenuation process of a transmitted signal, be it sound, microwave or light, or other electromagnetic radiation. Nuclear radiation density methods also fit into this class. The mass concentration can be determined and then if particle velocity can be related to gas velocity the mass flow rate can be calculated. (See appendix B)

Perhaps the most novel method noted in the

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*Velocity in the sampling tube is equal to the velocity in the flow conduit from which the sample is taken.

literature for measuring two-phase flow involves a nozzle with a sudden expansion section. Ackerman[1] used a nozzle of this design to develop a Solid-Liquid Flow Meter. He solved the momentum and energy relationships simultaneously and was able to determine total discharge as well as solids discharge from the nozzle.

Some recent foreign articles[3,36] appear from their abstracts to contain information that might be useful in developing a solid-gas flow meter. Barth[3] claims to have developed a new measuring nozzle, which from the diagram in his article appears similar to the meter developed for liquid-solid flow by Ackerman.

4. DESCRIPTION OF THE EXPERIMENTAL EQUIPMENT

This research was somewhat unique for a master's thesis project in that the experimental work was carried out in a full scale operating power plant. Advantages of this large scale research were: flow, temperature, pressure, and particle conditions conformed exactly to those of an actual plant. It would have been difficult to achieve this in a laboratory. Stochastic factors present in the operating power plant also graphically displayed equipment malfunctions that would not have been discovered in the laboratory. Chief disadvantage encountered was that the operating personnel had to meet the power load and routine maintenance requirements before experimentation could be conducted.

4.1 Circular Pitot-Sample Tube

The circular pitot-sample tube is shown in Figures 3 and 7. This tube is of the author's design and was an attempt to construct a device that could characterize two-phase flow much like a pitot tube characterizes single phase flow. The device constructed by the author should work on both gas-solid and liquid-solid flow, although it was only tested on the former.

The pitot-sample tube consists of an aluminum tube one and one-eighth inch in diameter and approximately twenty inches long with a rectangular 7/8 x 5/8 inch notch in one end (see Figure 3). An aluminum asymmetrically tapered plug fits in this end and seals the tube except for a rectangular hole. Two pressure taps are also installed in the tube assembly. One on the outside measures static pressure in the flow conductor and is perpendicular to the large rectangular hole which faces into the flow. The other tap is located inside the tube and measures the pressure rise within the tube. (This is the stagnation pressure if the open end of the tube is blocked).

In operation the pitot-sample tube can function in either of two possible configurations, with the end opposite the rectangular hole open or closed.

With the open end of the tube blocked, it responds like a pitot tube with a somewhat lower coefficient (0.67). (The coefficient proved to be constant over a wide flow range much like a regular pitot tube; see Figure 9). For two phase operation it was found that although the pressure in the tube rose immediately to a constant value, the large opening and the volume of the tube prevented plugging until reliable pressure readings could be obtained. It was then a simple matter to blow compressed air through the tube removing the solid material, thereby making continued measurement possible.

With the open end of the tube connected to separation equipment as described below, it was possible to aspirate the separation equipment and tube so that the pressure inside the tube was equal to the pressure in the flow conduit as measured by the outside tap. In this condition none of the kinetic energy of the fluid flowing in the conduit was being converted to potential energy in the form of pressure difference; hence, the fluid flowed into the tube as fast as it flowed in the conduit. This procedure is called isokinetic sampling. With this mode of operation it was possible to sample a portion of the two-phase flow in a large conduit without disturbing the flow patterns or causing a segregation of the phases. Separation equipment described below was then used to segregate and measure the individual phases.

4.2 Additional Equipment

Along with the pitot-sample tube it was necessary to have equipment to separate and measure the individual phases. Figure 2 is a schematic diagram of the separation apparatus used and Figure 6 is a photograph of it. The pitot-sample tube is connected with 1 inch I.D. tygon tubing to a short section of copper tubing extending from a cyclone collector. The effluent gas from the cyclone then runs through a cotton filter and to a rotameter which measures the air flow. Coal flow is determined by weight collected per unit time from the cyclone. An air ejector follows the rotameter and is used to control the pressure in the tube so that the flow is isokinetic.

Several purge points were included as shown and by proper closure of valves the system could be freed of coal after a measurement period. All fittings and tubing transporting the coal-air mixture were sandblasted to remove roughness and prevent accumulation of coal. Thermometer and pressure taps were also located as shown. The wet and dry bulb thermometers after the cotton filter made it possible to determine relative humidity at any point in the system where the temperature was known. This was done by using a standard humidity chart and making the assumption that no water escaped from the system.

A pressure test was conducted on the whole sample apparatus and leaks were stopped so that the equipment would hold air at 10 psi for an extended period of time. This was considered adequate proof that only the air entering the sample tube would pass through the rotameter.

Coal samples were weighed on a two pan balance with an accuracy of 0.1 g. and coal volume measurements were made with graduated cylinders.

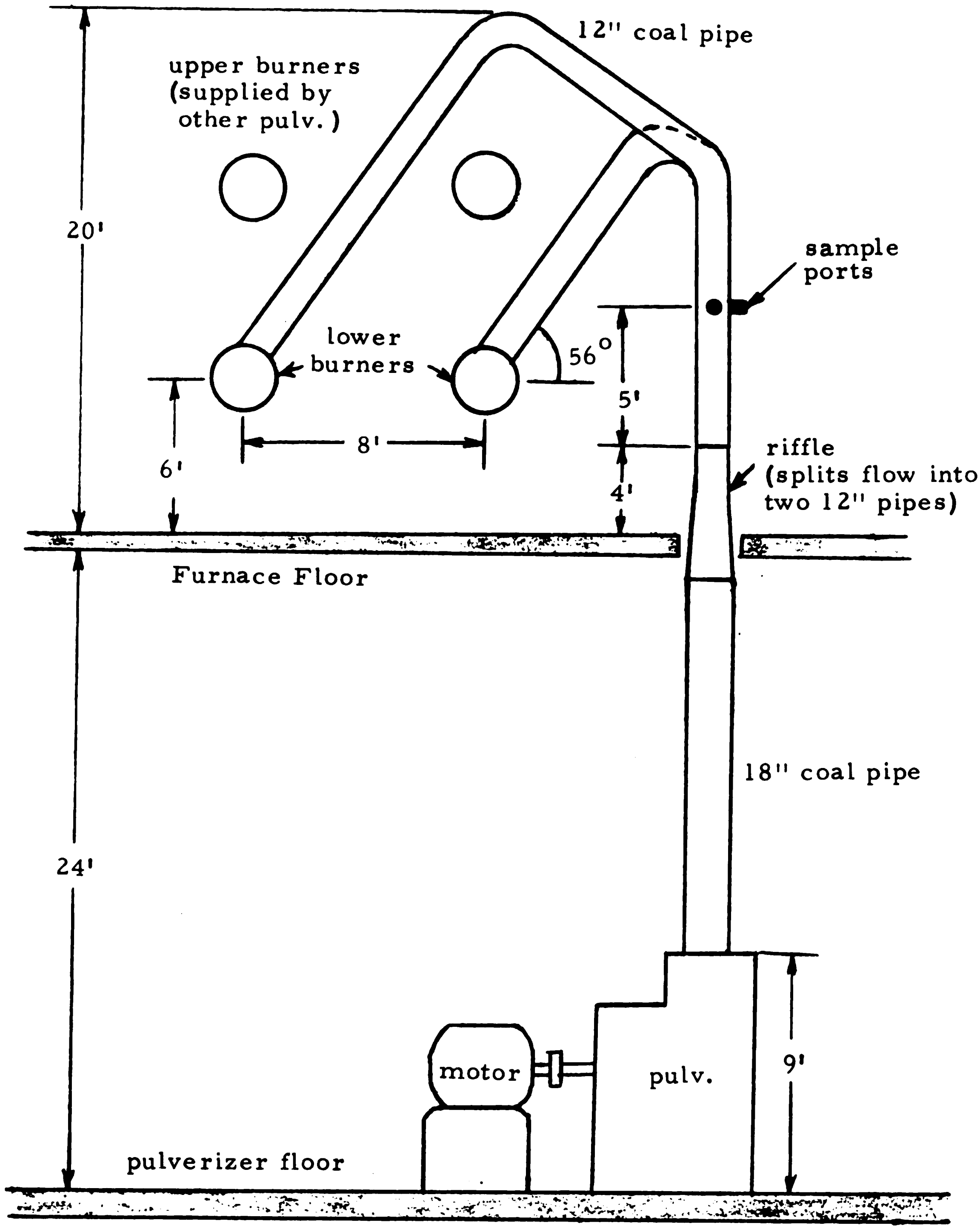
Pressure drop across a section of burner fuel line (used in total input-output study) was determined with a Leeds and Northrup Flow Transmitter. Full scale deflection of this particular transmitter was five inches of water and it gave trouble free performance. Figure 8 is a photograph of the pressure sensing cell and recorder.

4.3 Power Plant

Michigan State University Power Plant 65 is a steam and electrical generating plant. Two 250,000 lb. per hour, two drum, single pass boilers and tangent-tube furnaces are coupled to two fully-condensing, single-automatic extraction steam turbines, with direct connected generators and exciters. Each boiler-turbine generator is capable of operating entirely independent of the other boiler-turbine generator. This was helpful in the present study in that one of the boilers could be essentially isolated from the power system by setting it at a fixed output and meeting load fluctuations with the other boiler.

The plant is operated from a central control room from which start-up, shut-down, and load variation adjustments can be controlled.

Coal is delivered to the plant by railroad and stockpiled on the site. A series of belt conveyors transport the coal to bunkers with a 1,600 ton capacity. At full load consumption of 24 tons per hour this is almost a three day supply. Therefore, it should be noted for future study that the weater effect on input coal (see section 8) is governed by a large time constant. The coal flows by gravity from the bunkers to automatic scales which are set for two hundred pound dumps. Following the scales are feeders that provide a constant flow to the Riley Pulverizers. From each pulverizer the coal travels 20 vertical feet to the furnace floor where the flow is split by a riffle (Figure 4) and then enters the furnace through two burners (Figure 5).



Front Elevation

Figure 1. Furnace I - coal pipe, Michigan State University Power Plant 65.

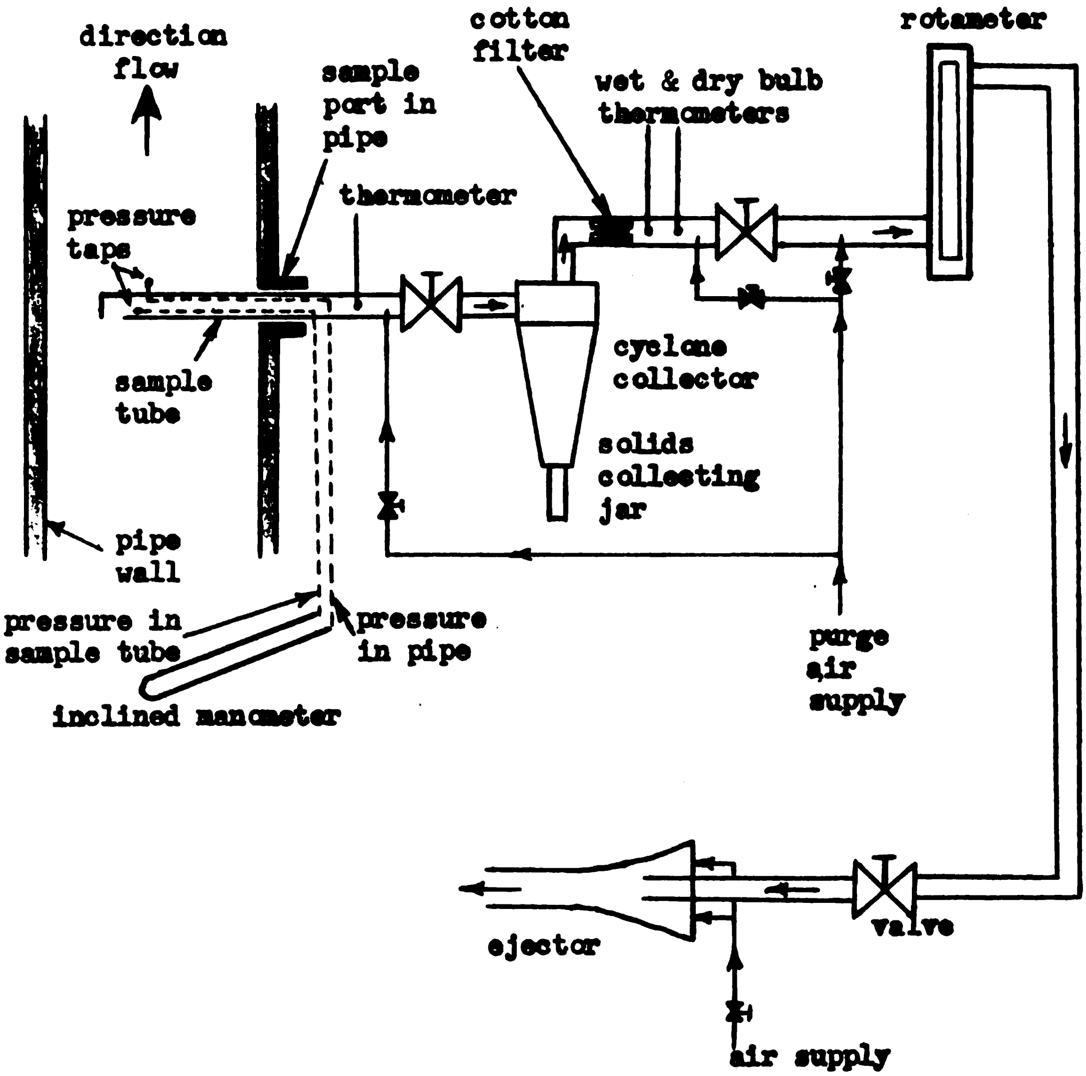


Figure 2. Isokinetic Flow Measurement Equipment

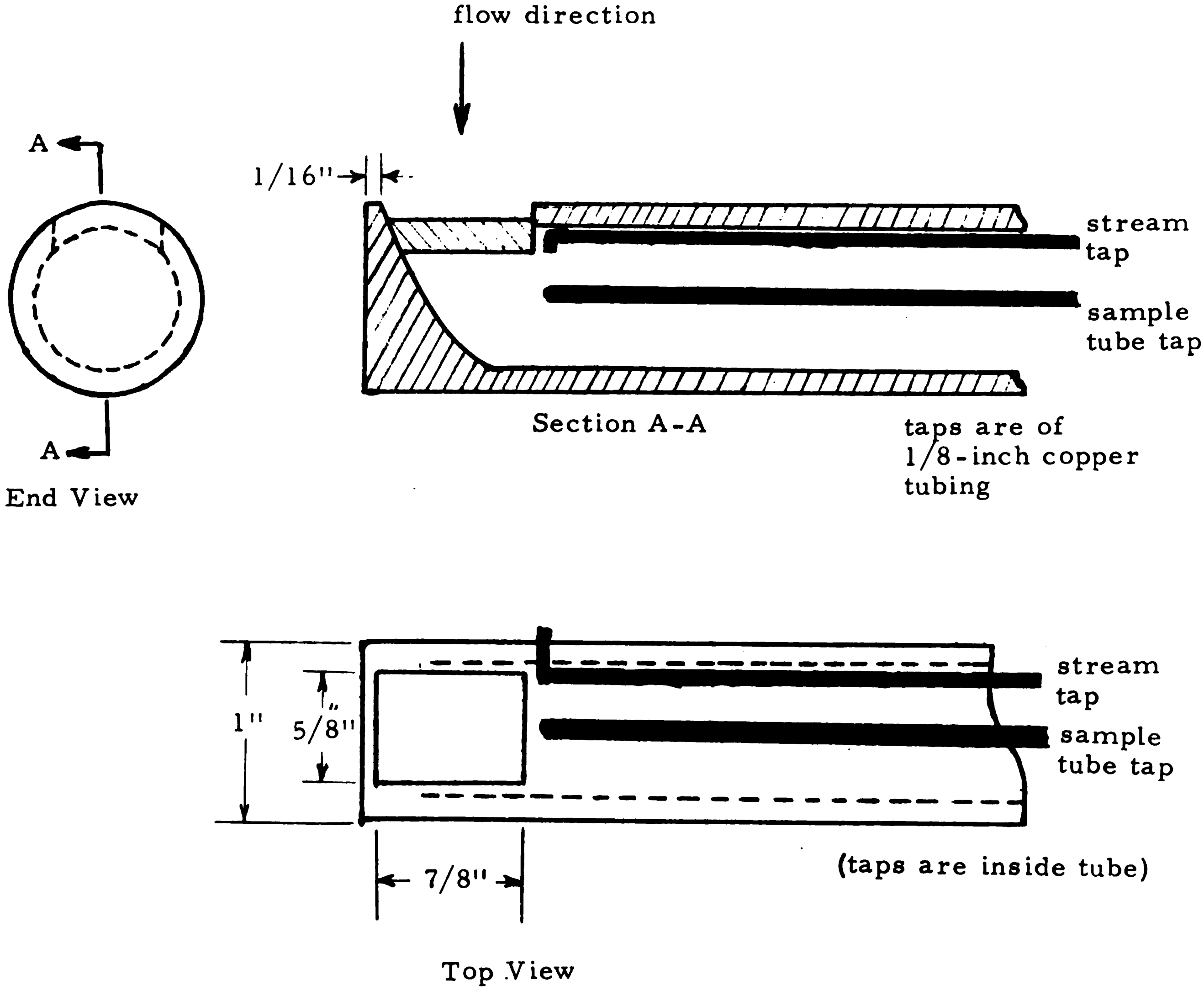
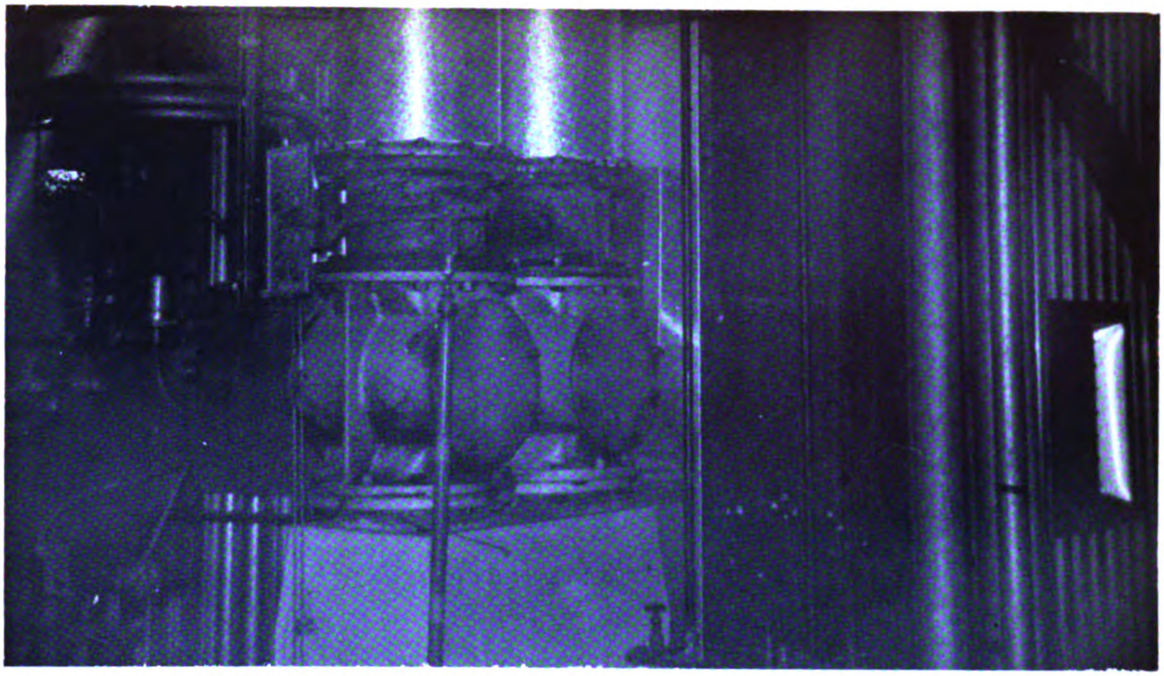
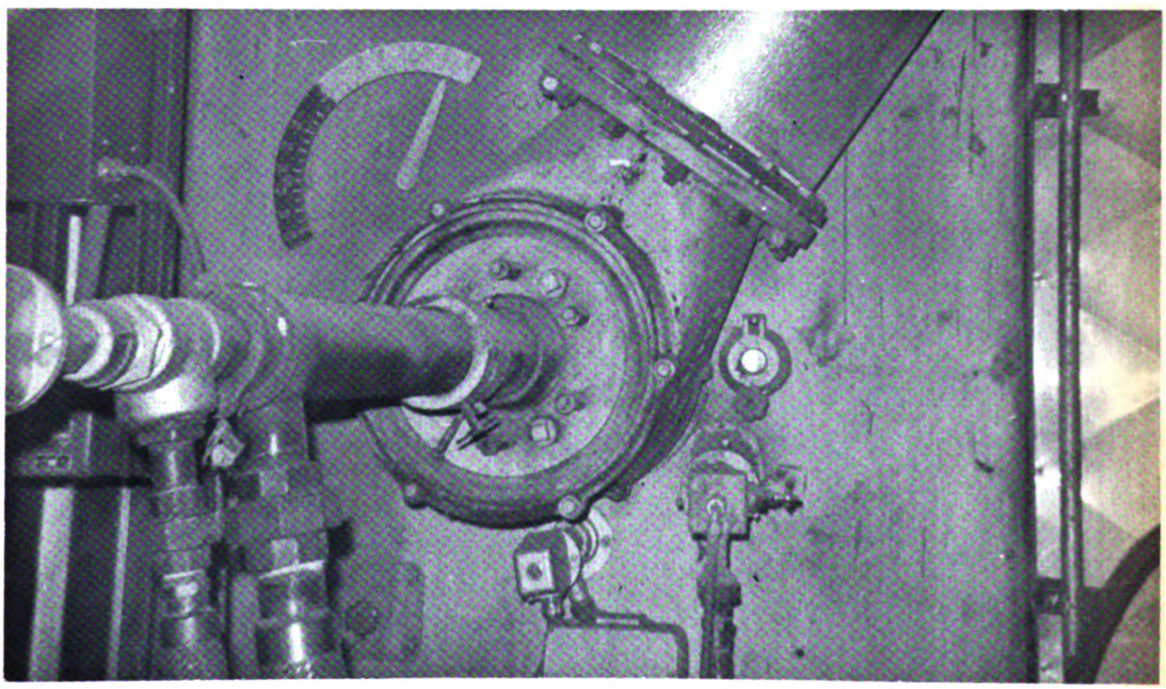


Figure 3. Isokinetic Sample Tube.



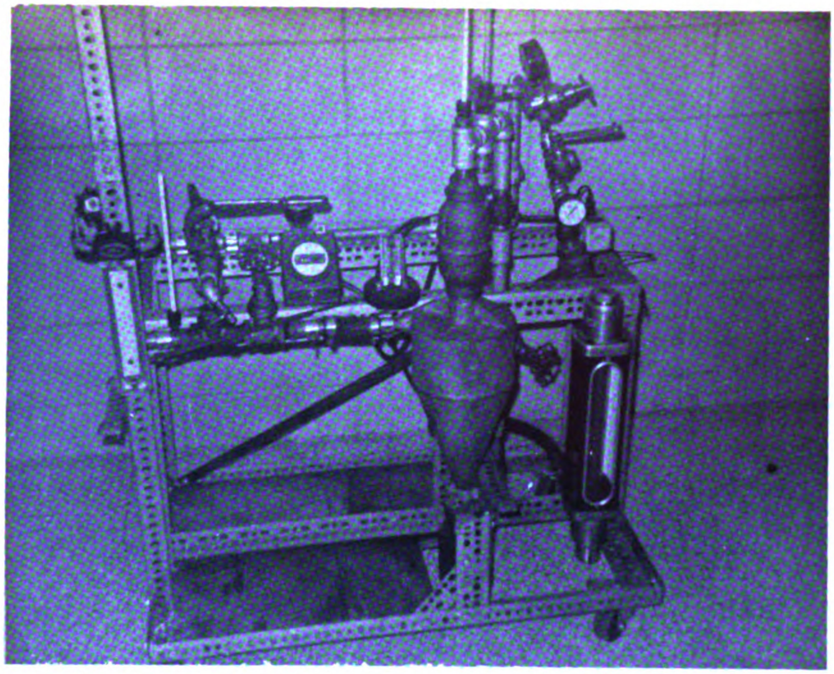
Twelve Inch Fuel Lines Leaving Riffle

FIGURE 4



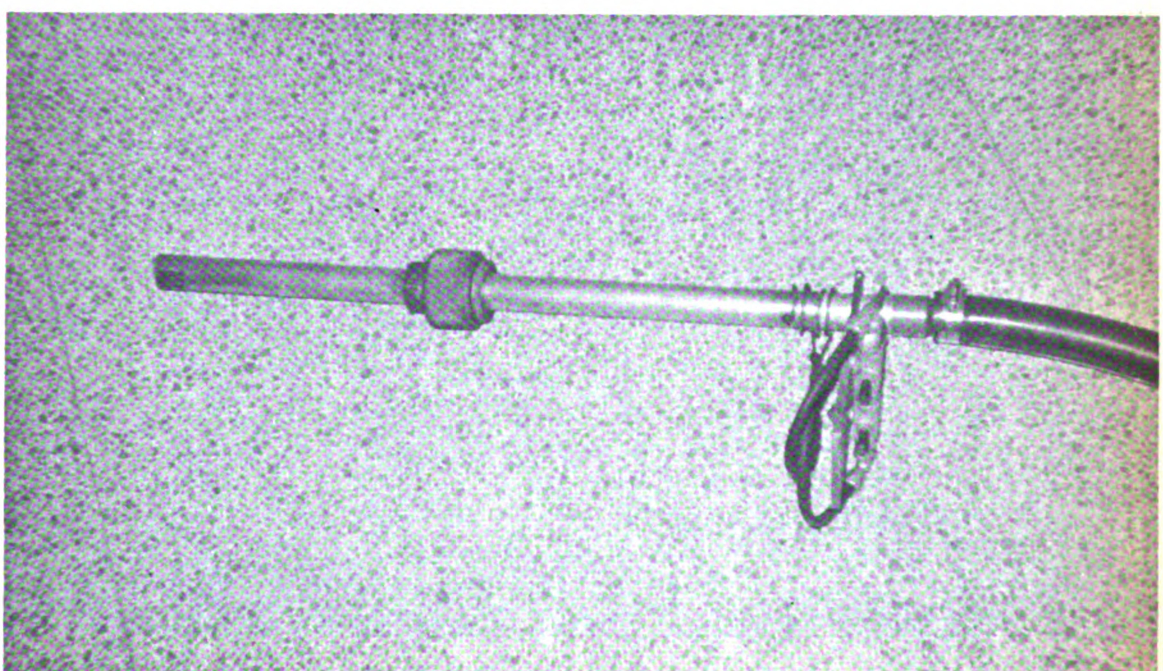
Twelve Inch Fuel Lines Leaving Riffle

FIGURE 5



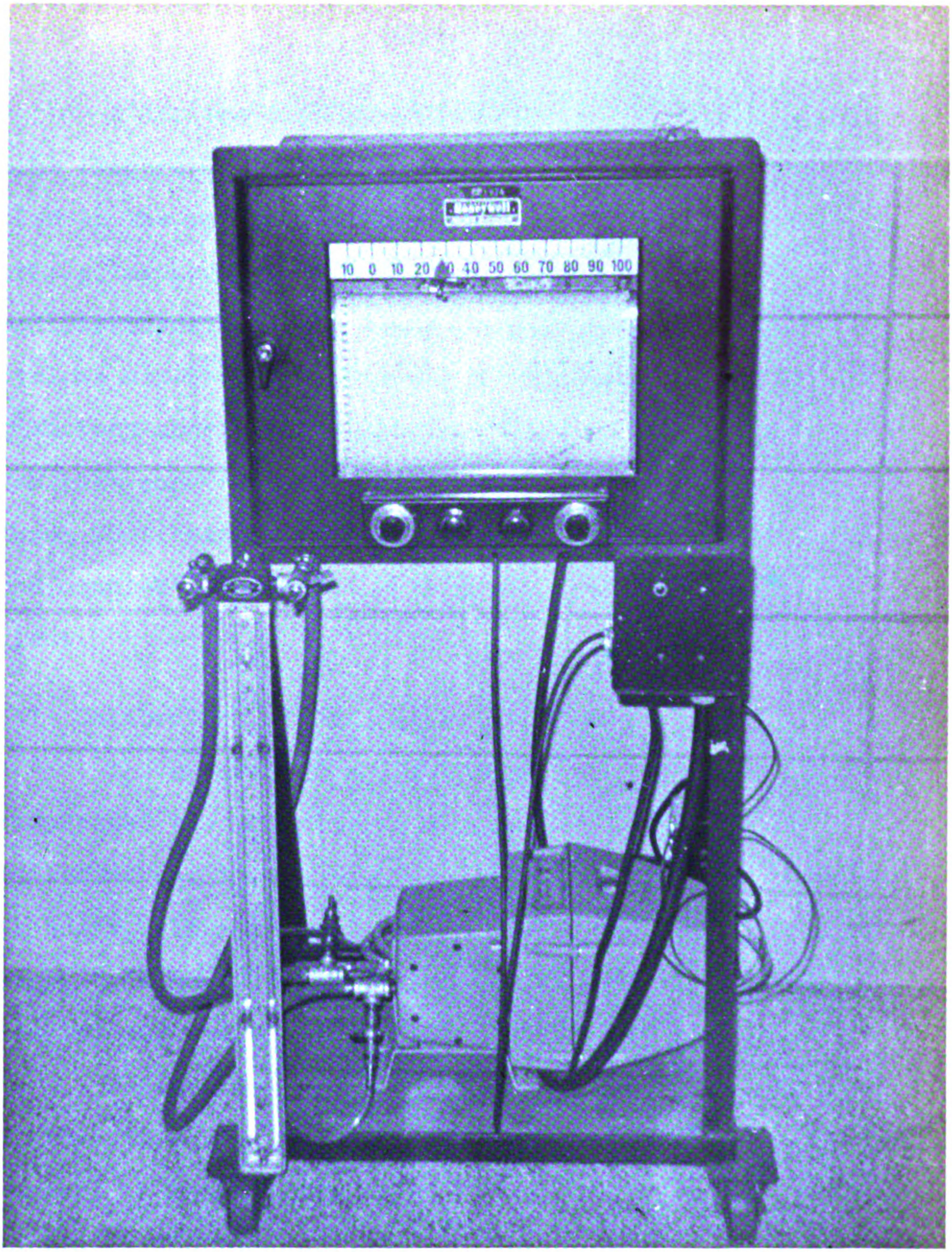
Isokinetic Flow Measurement Equipment

FIGURE 6



Isokinetic Sample Tube

FIGURE 7



Differential Pressure Measurement Equipment

FIGURE 8

5. EXPERIMENTAL WORK

After the initial design of the separation equipment (Figure 2), the major pieces of hardware were assembled in the power plant and trial samples taken. These trials, although qualitative in nature, suggested design modifications. One of these, a cotton filter after the cyclone separator, is visible in Figure 6. All the modifications considered necessary were made and the equipment was then constructed in a permanent form on a two foot by three foot chasses. This chassis was sturdily constructed and mounted on casters for easy movement about the power plant.

5.1 Calibration of Equipment in One-Phase

The separation equipment was tested for leaks with compressed air and after some seals were replaced the equipment was able to hold a pressure of 10 psi for several hours. This is considerably above the operating pressure, 8 inches of water, and insured that none of the sampled gas would leak before being measured.

Calibration of the sample tube with the end closed, a pitot tube, was done for two reasons. First, it was necessary to learn something about the aerodynamic characteristics of the tube. Did it perform, as intended, like the standard sharp edged pitot tube? Secondly, if the tube did behave as a pitot, it would be interesting to try and measure the gas velocity in this independent manner. For this velocity measurement a calibration would be necessary.

The calibration was performed at the end of a duct 10 inches in diameter and 15 feet long. A blower connected to a variable speed direct current motor provided air flow in the duct and made it possible to vary the velocity continuously to 300 ft/min. An accurate velocity measurement was made with a calibrated pitot tube that was permanently mounted in the duct.

Pressure differential measured with a pitot tube can be related to fluid velocity by Bernoulli's equation as follows:

$$V = C\left(\frac{2g_c}{\rho}\Delta P\right)^{\frac{1}{2}}$$

where

V = velocity

C = coefficient that is constant over a relatively large ΔP range

g_c = acceleration due to gravity

ρ = density of fluid

ΔP = measured pressure differential

Rewriting the above equation and including some constant factors for units conversion yields:

$$V = K\left(\frac{\Delta P}{\rho}\right)^{\frac{1}{2}}$$

where

$$V = \text{velocity, ft/min}$$

$$K = \text{coefficient in Figure 9}$$

$$\Delta P = \text{pressure differential, inches water}$$

$$\rho = \text{density of fluid, lb/ft}^3$$

Inspection of Figure 9 shows that in fact the sample tube does behave like a pitot tube, with K becoming constant at higher velocities. This indicates that the turbulence created by the cylindrical sample tube at its opening has negligible effect on the pressure measurements.

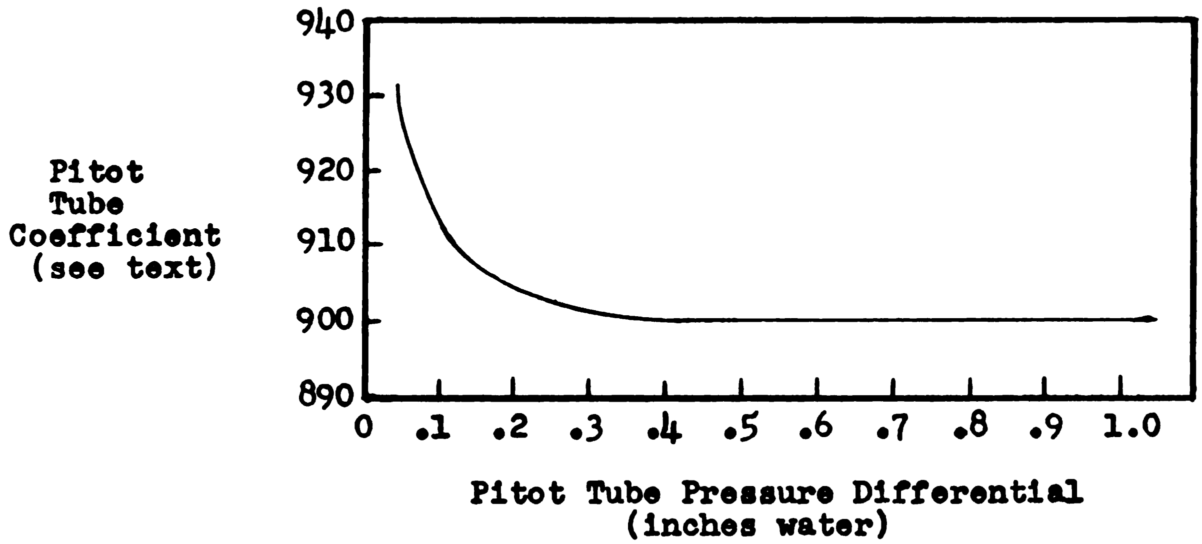
Limited experiments were conducted to determine the effect of tube orientation on measured pressure differential. It appears that a change of ten degrees from the perpendicular to the flow direction changes the measured pressure differential by only 2%. This is relatively small change compared to that of a normal pitot tube.

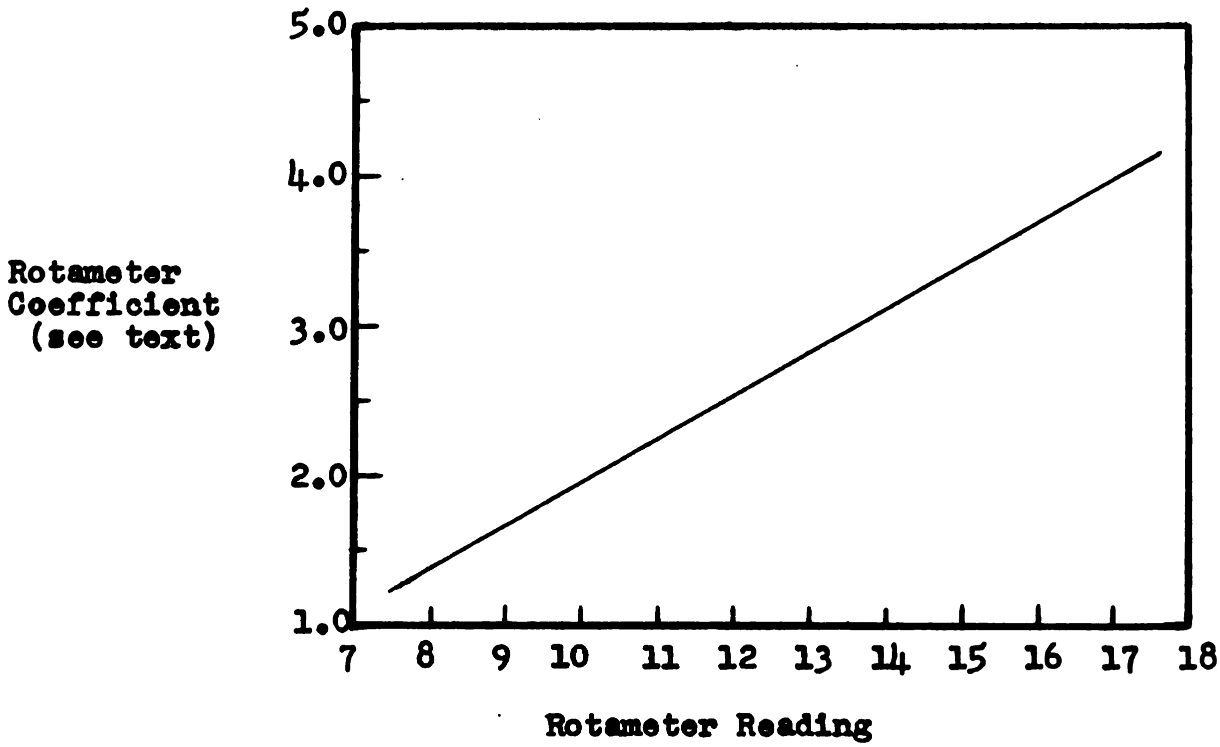
As mentioned earlier a rotameter was used to measure the air flow rate in the isokinetic sampling equipment after the coal had been removed by a cyclone separator. The flow rate through a rotameter can be described as:

$$W = CD_f \left(\frac{W_f(\rho_f - \rho)\rho}{\rho_f} \right)^{\frac{1}{2}}$$

where

$$W = \text{mass flow rate}$$





Calibration Curves For Flow Measurement Equipment

Figure 9.

C = coefficient dependent on height of float in rotameter

D_f = diameter float

W_f = weight float

ρ_f = density float

ρ = density fluid

The density of the steel float used in this rotameter is 100 lb/ft^3 and that of the fluid (air) never exceeds 0.08 lb/ft^3. Hence, the above equation can be reduced to:

$$W = K \rho^{\frac{1}{2}}$$

also

$$W = q \rho$$

where

W = mass flow rate, lb/min

K = coefficient dependent on height of float in rotameter, Figure 9

ρ = density fluid, lb/ft^3

q = volumetric flow rate, ft^3/min

Calibration of the rotameter in the same variable air speed duct used before yielded a linear relationship between K and the rotameter reading, Figure 9. The calibration was performed by operating the isokinetic sample equipment exactly as one would in a two-phase flow situation. Thus, the linear profile of Figure 9 not only indicates that the rotameter was functioning as designed but also that it is possible to operate the sample tube isokinetically by aspirating the tube and equipment so that the pressure inside the tube is equal to that outside.

5.2 Flow Profile Measurements

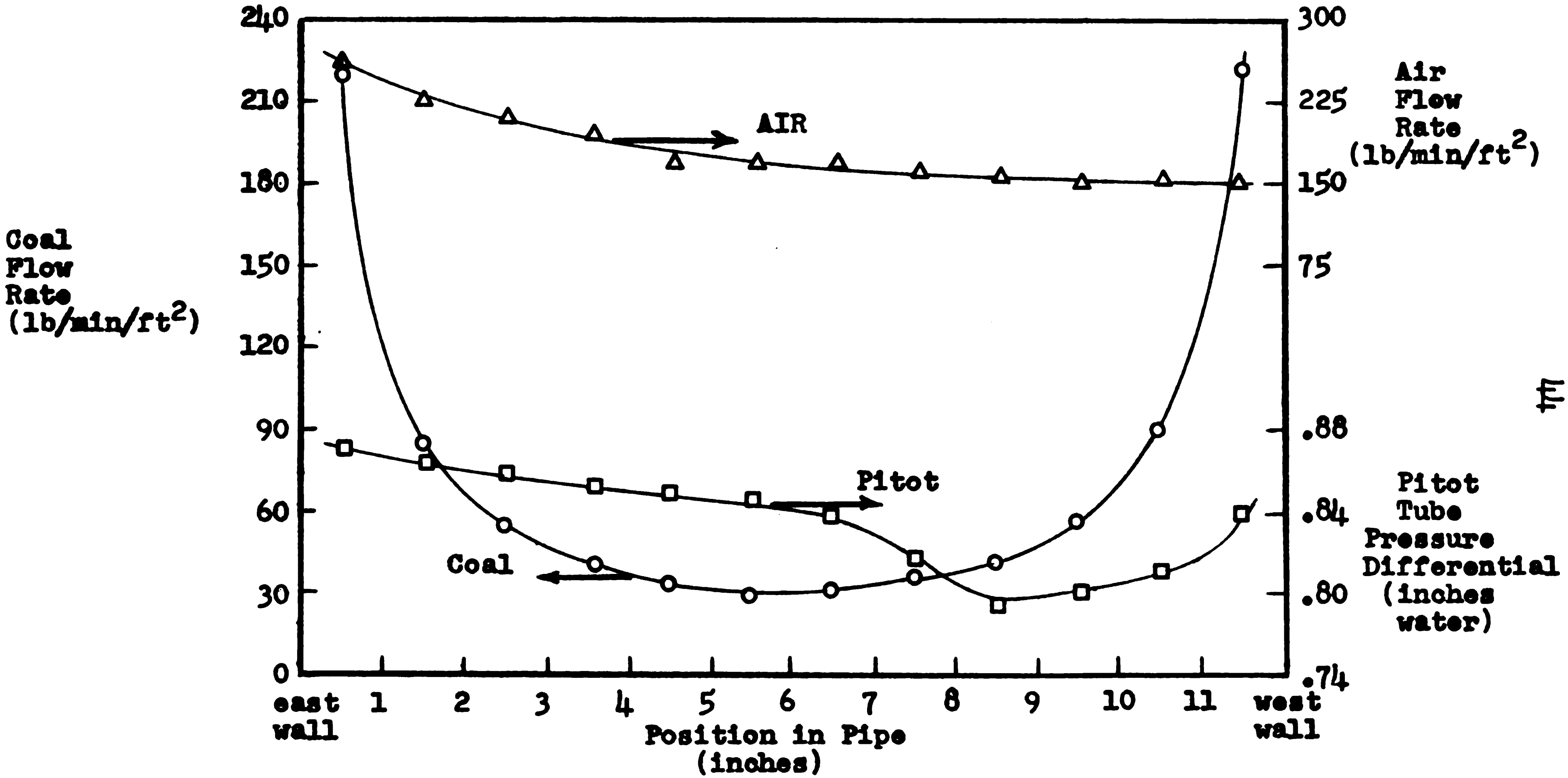
All flow measurements were taken on the 12 inch upper burner fuel line of Furnace I Michigan State University Power Plant. The physical layout of the line is as shown in Figure 1. The sample ports were located five pipe diameters above the riffle and four pipe diameters below a 45° bend. The ports were positioned at right angles to each other and it was therefore possible to obtain East-West (Figure 10) and North-South (Figure 11) profiles.

Experimental measurements of velocity profiles were made by putting the pulverizer in the manual operating position and leaving it at a fixed set point. This permitted the author to make point flow measurements in the steady-state stream. Each point measurement takes about six minutes.

It was quite easy to maintain the sample tube in isokinetic operation by adjusting the air supply to the aspirator until an inclined manometer indicated zero differential pressure across the tube. Once the air supply was adjusted only small periodic changes were required to maintain zero pressure differential. Thus, coal flow measurements, obtained from amount of coal collected per unit time, could be made withrelatively good precision and ease. On the other hand, air flow rate was determined by reading the height of the float in the rotameter. The float tended to oscillate and it required skill to obtain precise readings.

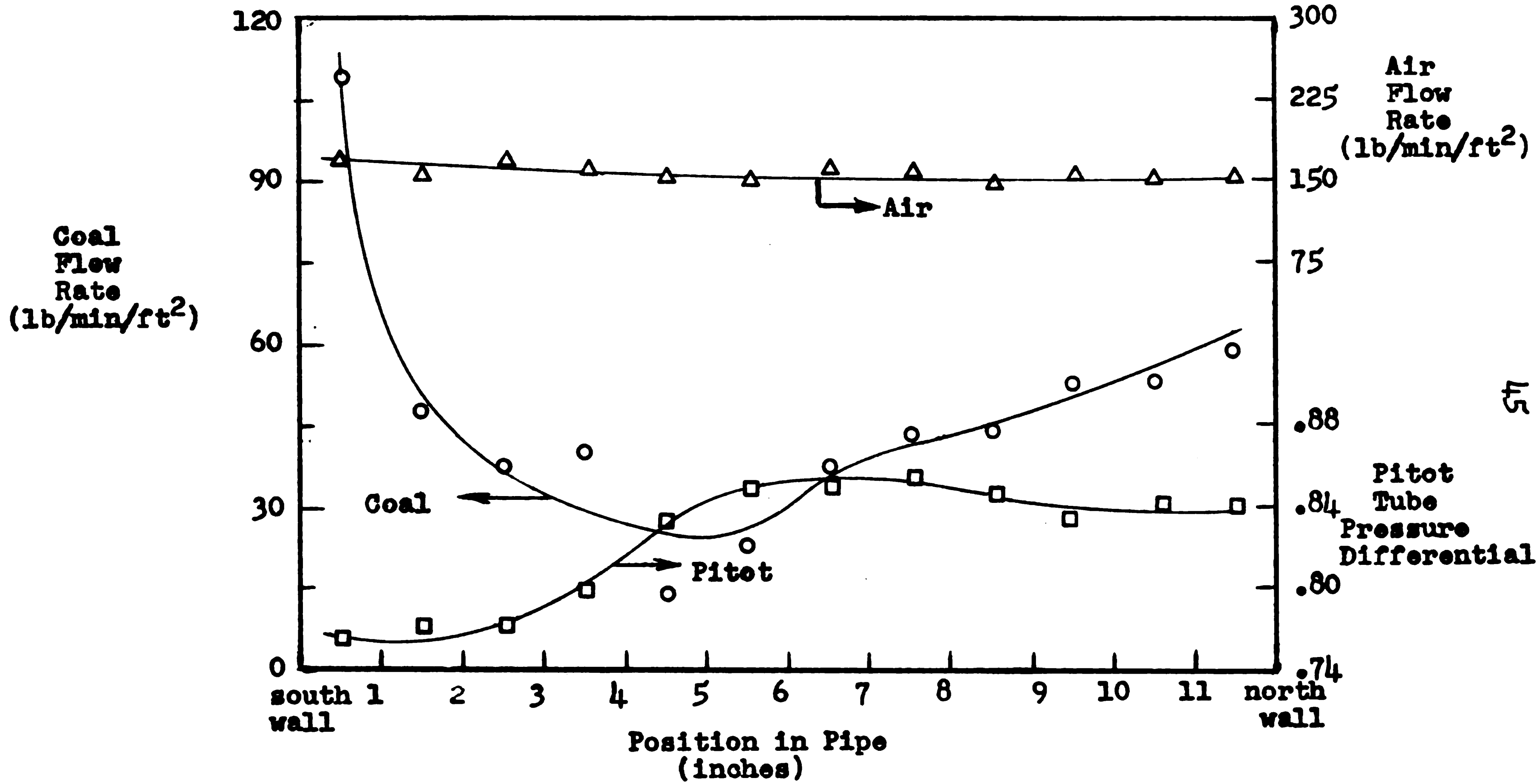
Because of the difficulty encountered in obtaining air flow rates, pitot tube differential pressure measurements were taken. These were obtained by clearing the tube with compressed air and then monitoring the differential pressure across the tube. Typically, the pressure would rise and reach a constant value for about one minute before the tube became plugged with coal, resulting in an erratic reading. Unfortunately, the pitot tube profile in the pipe (Figures 10 and 11) did not correspond to the air profile obtained from the rotameter. It appears that the reason for this is that the coal contributed to the differential pressure reading, making it an uncertain combination of two flow rates. Hence, the pitot tube shows little promise as a two-phase measurement instrument.

Figures 10 and 11 show the velocity profiles obtained in the burner line discussed above. The abscissa represents distance along the 12 inch profile while the ordinate is a flow rate measurement. For coal flow the scale on the left side of each figure is used as shown by an arrow. Air flow rate is read from the top scale on the right side. At conditions within the pipe the air density is 0.0652 lb/ft^3 and an air flow rate of 150 lb/min/ft^2



East-West Velocity Profiles

Figure 10.



North-South Velocity Profiles

Figure 11.

corresponds to a velocity of 2300 ft/min. Hence, air velocity can be obtained from the figures. Pitot tube pressure differentials taken as described above are also given in Figures 10 and 11 on the bottom scale, right side. The differentials were not converted to velocities by using Figure 9 since the figure is for air alone and the coal particle flow apparently influenced the pressures.

5.3 Total Boiler Input-Output Measurements

To correlate the velocity profiles shown in Figures 10 and 11 with total coal flow rate or steam output of a boiler is a difficult task. Several of the references listed in the bibliography[9] indicate that large errors can be expected whenever point measurements of even an accurately known profile are integrated to yield total flow rate.

However, a trial calculation was performed to obtain an approximate total flow rate in the burner line based on the profiles presented in Figures 10 and 11. A graphical integration of these profiles indicate that the average coal flow rate is about 3.0 times the center line flow rate. During a given one-half hour period the center line velocity was measured to be 32.2 lb/min/ft^2 and information from the automatic dump scales indicated a flow rate of 168 lb/min (± 15%) to the pulverizer. This would be 84 lb/min to each burner line. The average velocity for the 12" diameter pipe is calculated to be 76 lb/min, based on the center line velocity. This exceptionally close agreement seems to verify the profiles presented.

To correlate the boiler output in pounds steam per hour with the center line velocity would require additional measurements over a longer time period. However, the author believes this is quite possible and that very close correlation can be obtained.

5.4 Time Constant and Humidity Experiments

In addition to the major research for this thesis some supplmental work was done to provide a starting point for subsequent studies dealing with other phases of the Detroit Edison Company power plant control system project.

Gross observations involving response time were made in an effort to learn about the time constants associated with the power plant. A 10 percent step increase in the boiler output at a steam rate of 220,000 lb/hr caused the steam temperature to immediately drop 4°F and it took five minutes for the boiler to again reach steady-state. The power plant is also sensitive to weather conditions. A summer rain was noted to drop the outside air temperature 5°F in a few minutes with a corresponding decrease in steam temperature of 8°F in 15 minutes. These are just examples of the important role played by the dynamic response characteristics of a power plant. Simpkin[32] has simulated components and portions of these systems by synthesizing transfer functions from step response data. His models are more convenient to study than an actual power plant because timescaling accelerates testing and normal plant operation is not interrupted.

Moisture in the coal entering a power plant can greatly affect its operation. During winter it is a common practice to mix some of the hot flue gas with the air going to the pulverizers to maintain the fuel line temperature. This extra heat introduced is largely needed to vaporize water that enters with the coal. It would be interesting to monitor fuel line humidity year around and compare it with apparent heating value of the coal used.

Pulverizer outlet temperature was constant at 175°F all during this research and the air-coal mixture at the sample ports measured 145°F. Humidity was determined in in the sample apparatus with wet and dry bulb thermometers after the coal was separated out and the air temperature reduced to approximately 105°F. A psychrometric chart[35] can be used to relate the humidity at 105°F to that in the fuel line provided the air is not at its dew point (indicating moisture has condensed out in the sample equipment). Relative humidity was found to range from 50 to 75 percent in the sample apparatus, corresponding to 15 and 25 percent at the 145°F temperature of the fuel line.

6. DISCUSSION

It is important to remember that the velocity profiles and other measurements presented in this thesis were taken in a particular operating power plant. For this reason the actual values reported are probably not universal but indicate trends that are more widely applicable. Also the measurement techniques should be applicable to two-phase flow situations in general.

6.1 Correlation with Other Two-Phase Measurements

The literature on two-phase flow discusses relative flow rates of the solid and gas phases on an average basis.[33] However, from Figures 10 and 11 it can be seen that the ratio of solid to gas velocity changes continuously across the 12 inch line studied. It is worth noting that the solids flow rate is lower in the center core (about 6 inches in diameter).

Comparison of Figures 10 and 11 shows that the coal and air point flow rates are a function of both radial and angular position. Since there are only two sample ports on the fuel line (90° apart) the angular dependence was not accurately determined and is not presented graphically. However, one can see that the flow rate next to the wall in Figure 11 is approximately one-half that of Figure 10. The most probable reason for this difference is the riffle located five pipe diameters downstream from the sample ports. Inspection of construction diagrams for the riffle show that it consists of parallel plates aligned in an east-west direction. These plates, which split the flow to the two burner lines, should not distort an east-west profile. This is the case of Figure 10, but a north-south profile (Figure 11) will show distortion if the flow is not evenly distributed by the plates. Uneven distribution by the riffle is characteristically a problem and Figure 11 seems to confirm the difficulty.

6.2 Flow Stability

Measurements of velocity were made with the pulverizer held at a fixed set point as described in section 5.1. This was done to insure constant coal and air flow in the fuel line so that the point measurements could be made on a steady-state velocity profile. However, because the riffle was located only five pipe diameters from the sample port the author was concerned that the flow might not be stable. If it tended to oscillate between several different profiles the individual point measurements might be taken from different ones. Fortunately, periodic replications of some of the point measurements indicated that this was not the case. The flow was stable.

6.3 Attainment of Objectives

This research has accomplished all the objectives outlined in the introduction. An isokinetic sample tube and associated equipment has been developed. This equipment was used to measure velocity profiles in an operating power plant and establish a relationship between air and coal flow rate.

7. CONCLUSIONS

The isokinetic two-phase sample tube and associated equipment has proven useful in determining heretofor unknown velocity profiles. These profiles can yield information about pulverized coal and air flow distribution following riffles and bends in large burner fuel lines.

The sample tube actually measures an average velocity over a relatively small area. It is used to provide information on gross movements of each of the two-phases and will not determine point measurements directly next to the pipe wall. However, it performs quite well in large diameter lines and is trouble-free in operation.

The most significant outcome of this research is discovery of the large mass flow rates of coal towards the wall of the fuel lines. It appears that the core (center 6" diameter section of 12" diameter line) carries only a small portion of the total coal flow while in the outer annulus the flow rates are high. This effect causes a classification of the coal particles, with the smaller ones moving to the center of the line (appendix A).

The air velocity profile at the point of measurement was discovered to be linear, rising toward the southeast quadrant of the pipe. The reason for this tilted profile in a turbulent flow situation is a riffle located only five pipe diameters downstream from the only available sample point. This difficult situation is typical of the problems encountered in an operating power plant.

It appears that this isokinetic sampling equipment can be used as a calibration device for a continuous solid-gas flow meter as described in the introduction to this thesis. For calibration of a radiation density device it will be important to know about the non-uniform density in the pipe.

8. RECOMMENDATIONS FOR FUTURE WORK

One of the advantages of this flow measurement research is that it was conducted at an operating plant. In the plant stochastic factors sometimes led to situations that would not normally have developed in the laboratory. Most of these occurrences suggested interesting follow-up investigations, although not all of them would be pertinent to the present project. For brevity only three suggested investigations are outlined below.

8.1 Continuous Flow Measurement

It appears possible to continue the development of a two-phase mass flow meter as outlined in section 1 of this thesis. The major piece of new equipment required is a radiation density meter and it should be possible to select one of the commercially available types discussed in Appendix B. Section 5 contains data that will be necessary in specifying radioactive source intensity and detector type.

The apparent collection of larger size particles at the pipe wall is a phenomena that should be studied to insure accurate flow rate measurements with the density by radiation technique. However, it is anticipated that this effect can be accounted for by proper calibration with the isokinetic sampling tube. Variable water content of the coal in the fuel line may also be a problem since the water will absorb an undetermined amount of radiation. Calibration at different coal moisture levels will indicate the magnitude of this effect.

8.2 Coal Heating Value Measurements

The determination and monitoring of on-line fuel energy value is a complex problem. Initial observations indicate that for a plant operating on coal from a single source the moisture content of the coal may be the largest factor influencing heating value. A test of this could be made by comparing the apparent heating value of a given shipment of coal both before and after a rain.

The rate of change of the coal heating value is also an important consideration in the development of a control system. In a separate study for the Detroit Edison Company, samples of pulverized coal were taken from a fuel line at intervals of three minutes for over an hour. The heating value and moisture content of these samples is now being determined and this data should provide an indication of the sampling interval necessary in a fuel control system.

8.3 Pulse Phenomena

During this research it was noted that fluctuations occurred in differential-pressure measurements across the fuel lines carrying pulverized coal and air to the burners.

A search of the literature indicated that Knudsen and Olsen[19] had observed similar fluctuations in pressure measurements across fluidized beds. Following a method established by Sutherland they were able to obtain a direct indication of particle size in a fluidized bed by measuring the intensity and frequency of the fluctuations.

Their method consists of numerically expressing, in arbitrary units, the sinuosity or length of the differential-pressure trace over a specified time. An average particle size is then obtained from this measurement by an initial calibration with particles of a known size. Knudsen and Olsen give a method for continuously recording the length of trace per unit time.

It may be possible to obtain similar measurements of average particle size in the pulverized coal-air lines of a power plant. These measurements would at least give a qualitative indication of any changes in particle size.

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APPENDIX A

COAL PROPERTIES

In any particular solid-gas flow system the solid particles have a unique combination of physical properties that markedly influence the flow. The values of these properties can be more difficult to determine than might be expected. It is the purpose of this appendix to outline the information gathered on the two most important physical properties for the pulverized coal studied.

A.1 Coal Fineness

The accepted method of determining coal fineness is governed by ASTM Standard D197-30. A given sample is first separated by sieves and then the weight fraction of the total sample that collects on each sieve is determined and reported as in Figure 12. The size of the sieves used is somewhat variable, although the combination of a 200, 100, and 50 mesh sieve is common.

From Figure 12 one can see that the coal samples taken from the University Power Plant contain a large portion of particles smaller than 44 micron (-325 mesh). To characterize the samples adequately it would be desirable to classify these smaller particles. Unfortunately, standard sieving methods cannot be used for particles smaller than 44 microns. However, photographs (Figure 14) were taken to give a qualitative understanding of the particle size range involved and with this information it should be possible to select appropriate separation equipment.

Figure 13 is a graph of the particle size distribution (from Figure 12) across a vertical section of the 12 inch burner fuel line. It should be noted from this figure that the larger size particles tend to collect at the pipe wall while the smaller ones move toward the center. This may be an important effect and is certainly connected with the profiles for coal and air mass flow rate shown in Figures 10 and 11. Standard sampling techniques do not consist of point samples as discussed here but rather are collections of equal weight samples from equal increments of annular areas. The above classification effect coupled with the known velocity distributions would tend to make this standard sampling technique biased toward the larger particles. Perhaps, the easiest method for accurately monitoring characteristic coal particle size in a plant would be that outlined in section 8.3 of this thesis.

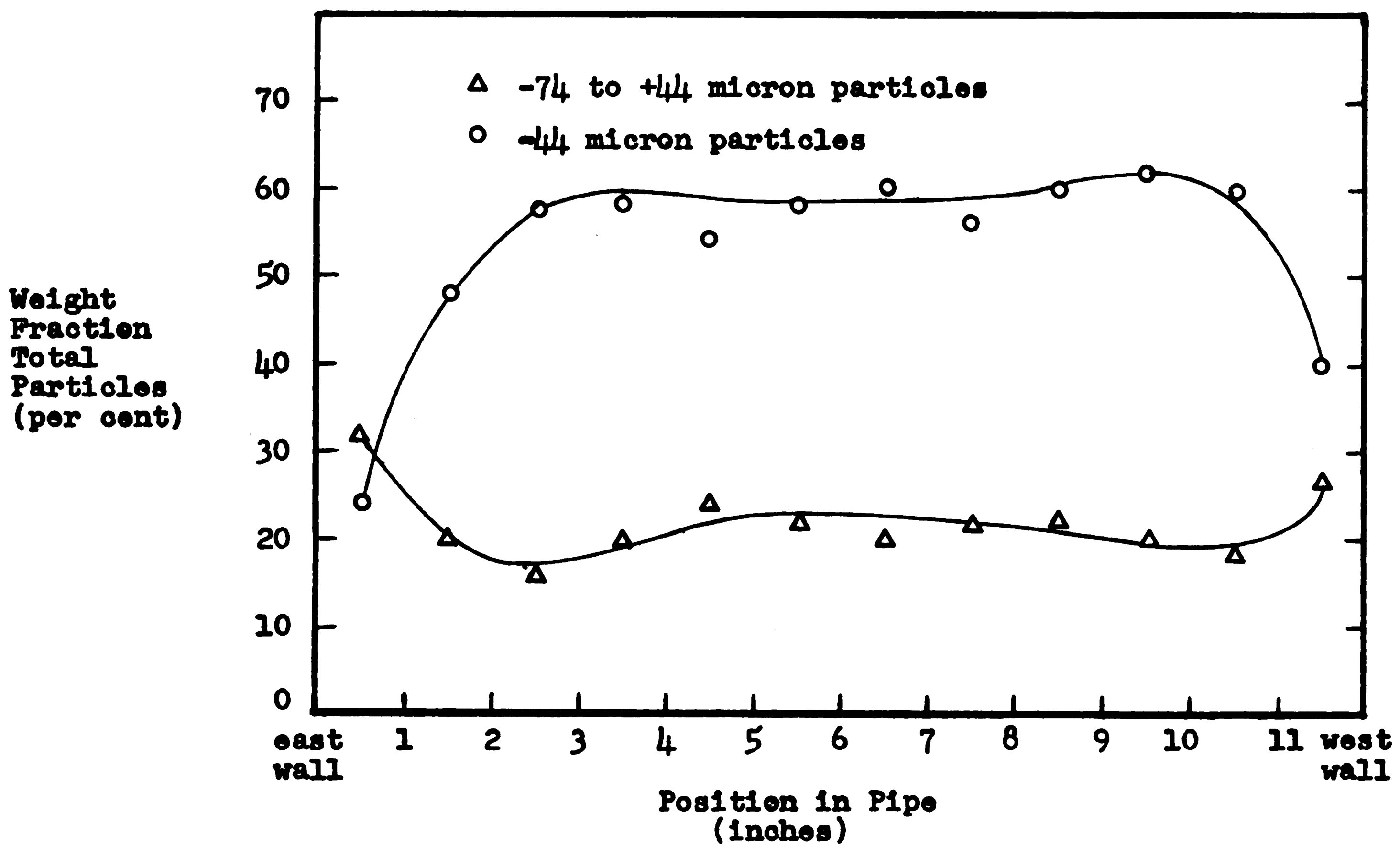
A.2 Coal Density

Bulk coal density was determined for this research by weighing a sample and then measuring its volume in a graduated cylinder. This method is commonly used in industry and yielded precise results.

TABLE OF COAL PARTICLE SIZE
DISTRIBUTION IN FUEL LINE

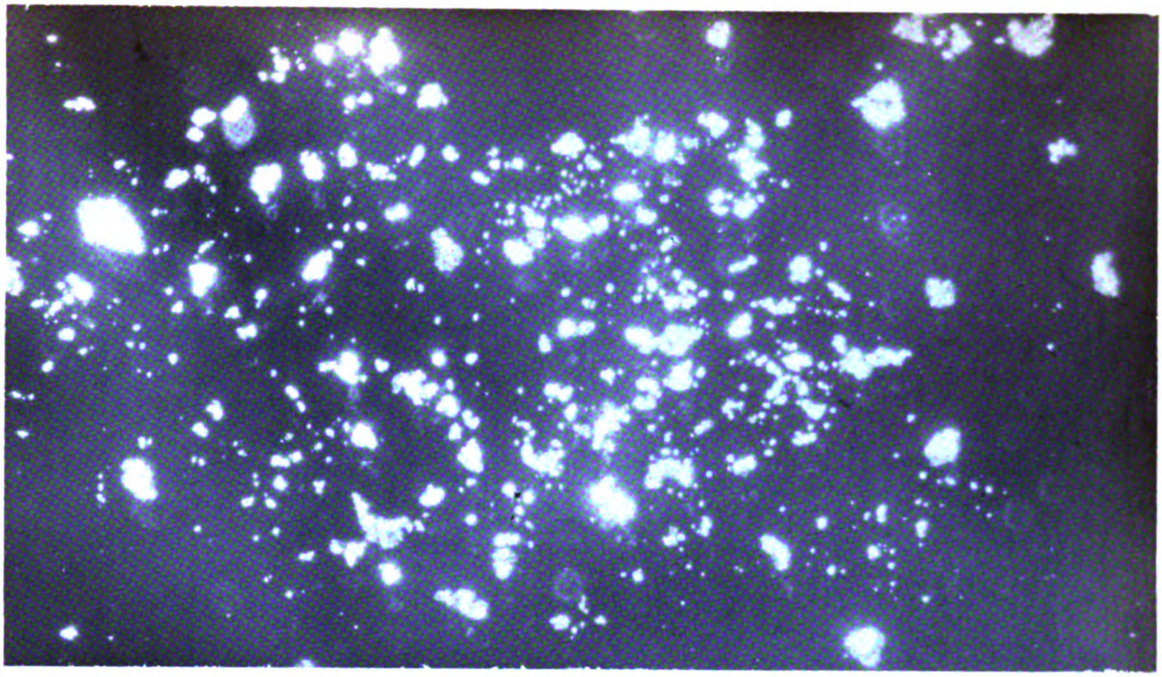
SAMPLE LOCATION	WEIGHT PERCENT GIVEN SIZE					
Sieve Size	+60	-60 +100	-100 +200	-200 +325	-325	Total
Particle Size (microns)	+250	-250 +149	-149 +74	-74 +44	-44	
Inches from East Wall of Line ½	2	14	28	32	24	100
1½	2	12	18	20	48	100
2½	2	8	16	16	58	100
3½	2	6	14	20	58	100
4½	2	6	14	24	54	100
5½	2	6	12	22	58	100
6½	2	6	12	20	60	100
7½	2	6	14	22	56	100
8½	2	4	12	22	60	100
9½	2	4	12	20	62	100
10½	2	6	14	18	60	100
11½	2	10	22	26	40	100
Mill Output (June 30)	2	10	12	22	54	100
Mill Output (July)	2	6	12	22	58	100

Figure 12



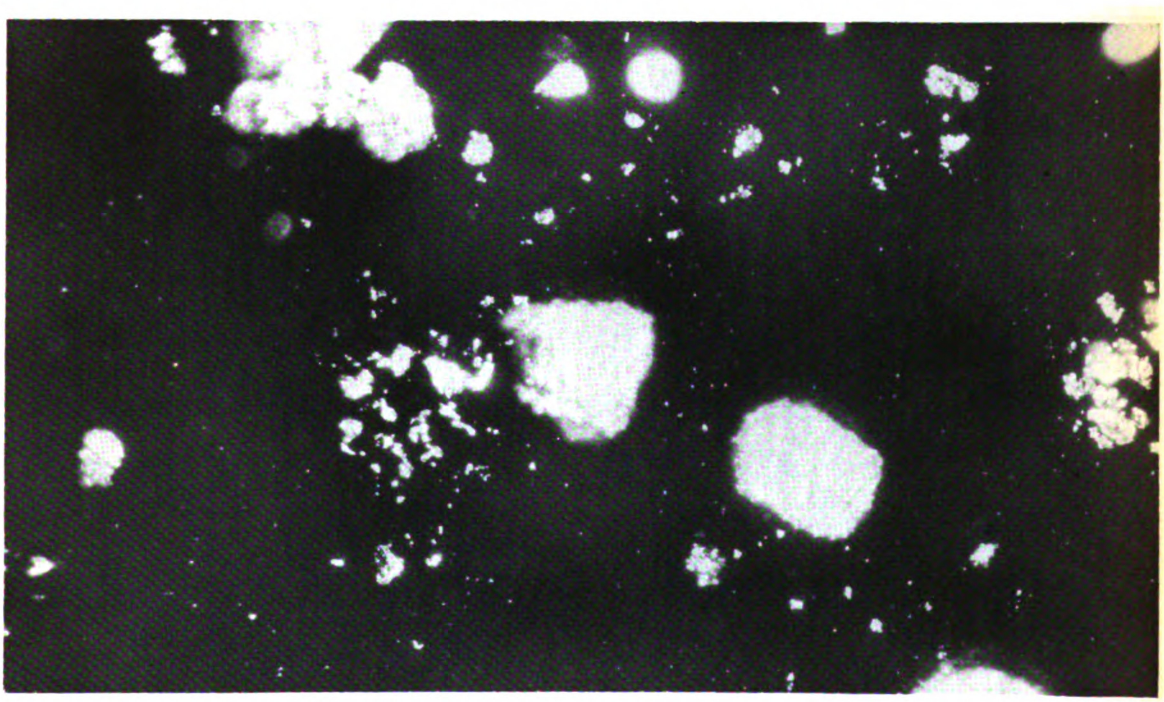
Profile Of Coal Particle Size In Fuel Line

Figure 13.



Typical Coal Particles Magnified 100X

FIGURE 14



Coal Particles Magnified To Show Shape

FIGURE 15

Coarse wet coal entering the pulverizers had an apparent density of 45 lb/ft^3. This density was for the slightly packed coal. On the other hand, pulverized coal samples from the 175°F fuel line taken after the riffle had a bulk density of 38 lb/ft^3. These results seemingly contradict the fact that there is more void space in the coarse coal sample. There are perhaps two factors that account for this paradox and they are discussed below.

The coal in the fuel line is much drier than that in the bunkers. This is particularly true with the very fine particle sizes since the rate of drying is directly proportional to the three-halves power of the particle diameter.[35] Any loss in moisture will cause a corresponding drop in density since the specific gravity of the coal is less than 1.

Another factor that may be more important in lowering density is swell of the coal particles due to contact with hot air in the mill and fuel line. Figure 15 is a photograph of magnified coal particles that was taken in an effort to identify any swelling. Although it is difficult to identify swelling, Figure 15 clearly shows that the surface of the coal particles are not smooth and would not pack as well as might be suspected.

APPENDIX B

ALTERNATE SOLID-GAS FLOW MEASUREMENT SCHEMES

The author believes that with the isokinetic sample tube calibration technique described in this thesis, it is possible to adapt commercially available equipment to the problem of continuously measuring coal-air flow in power plants. The instrument systems on which vendor literature was obtained, although widely varied, universally were developed as modifications of flow or density meters originally designed for measurement of incompressible (solid and/or liquid) media. The use of these methods to measure solid-gas flow will require special attention to undesirable characteristics which might make them difficult to use in the application under consideration. The systems are most easily grouped in two categories: mechanical and nuclear.

B.1 Mechanical Methods

The Foxboro Company of Foxboro, Massachusetts, markets a Force-Balance Target type flow meter. It consists of a circular square-edged target suspended concentrically, essentially forming an annular orifice, in the pipe carrying the flow. The target is connected via a rod to a "force-balance topworks" outside of the pipe which balances the force on the target and transmits it as either a pneumatic or an electrical output. The instrument also includes a silicone oil-filled mechanical damping device. It is available in four sizes that fit up to a 4-inch pipe. The instrument is adapted to different flow rate ranges by changing target size. B is defined as the "target-to-line ratio." (It is unclear whether this is the ratio of the diameters or the areas.)

Foxboro indicates that the flow rate equals a constant (K) times the square root of the force on the target. A graph is presented for K as a function of the pipe Reynolds number, B, and pipe diameter for gas or vapor flow. Inspection of these graphs for the 4-inch size shows that K varies widely over the whole range of Re for a B of 0.5, while for a B of 0.7, K is constant above Re = 2×10^3.

The bulletin "Special Coal-Air Target Flow Transmitter"[12] says nothing about actual experience in measuring coal flow and indicates that K should probably be determined experimentally for best results in each system. It seems this is essential. For the 12-inch pneumatic tubes under consideration very large forces and high pressure drops would result if the target-to-line ratios discussed in the bulletins[12] were used. However, reduction of target size would produce greater variations in K and lead to poorer measurements because of the flow distributions discussed earlier. These variations of K would also make the output difficult to linearize.

Another mechanical technique that might be suggested for in plant coal flow measurement is feeder drum revolution counting. The feeder is located in the raw coal line between the scales (or down spout from the bunker) and the pulverizer. As coal enters the feeder it drops into semi-circular pockets on the rotating feeder drum and as the drum rotates each pocket releases its coal into the pulverizer. Riley[30] and Semco[31] both indicate that their rotary airlock valves or feeders are a convenient means of "accurately and uniformly" feeding coal to a pulverizer although they give no quantitative indication of what accuracy is to be expected. A count of the number of revolutions made by the feeder drum per unit time plus knowledge of the pocket capacity would determine coal flow rate. Air flow would be determined by pressure drop in the burner fuel line. (Air flow rate could also be measured in the air supply duct to the mill, but most of these ducts have been noted to leak considerable quantities of air.) Chief disadvantage with this method of coal measurement lies in operation of the mill or pulverizer. Most mills do not operate on a fixed amount of coal and accumulation or depletion is constantly taking place so that a material balance cannot be used to calculate flow in the fuel line out of the mill.

Lastly, some mechanical devices have been developed

that could be useful if a small by pass line (say one inch) were taken off the main fuel line as a representative. Fluidynamics Inc. of Arcadia, California markets what they call a "new primary flow element" which measures the differential pressure caused by centrifugal acceleration as fluids pass through a circular loop inserted in the flow path. Of course, the difficulty would be to get a representative sample of the two-phase flow.

B.2 Nuclear Methods

Nuclear radiation methods in fluid flow studies can be subdivided into three groupings: flow rate by radioactive tracers, density by transmittance, and density by backscatter.

Hull[15,16] has written several articles on applications of radioactive tracers to determine flow rate in industrial plants. In the flow rate by dilution technique a tracer gas, such as Radon, is added to the test stream and samples are removed at various points and tested for concentration of the tracer, thus yielding total flow rate. This is probably the most expensive technique as far as radioactive material is concerned and might be dangerous in large pipelines where a substantial amount of tracer was needed. The total count method is used to determine flow rates and amount of backmixing in flow systems. A given amount of radioactive material is added and a detector determines the time required for the total

amount of tracer to pass a given point. The peak timing technique is considered by Hull to be the best for turbulent flow rate measurement. A quick pulse of radioactive material is added to the flow and the time required for the peak of the pulse to reach a point downstream determines flow rate. All the radioactive tracer techniques have two disadvantages in the present power plant situation: (1) they are not continuous and could be used only for periodic measurements, (2) considerable care would have to be taken to prevent radiation hazards.

Two companies make equipment to determine density by transmittance. In both these systems a source is located on one side of the process pipe while a detector is located on the other. The energy from a radioactive source that is transmitted to a detector is:

$$I = e^{-\mu \rho t}$$

where μ = coefficient of absorption

ρ = density

t = thickness of material

Thus, absorption of radiation is dependent upon the coefficient of absorption as well as density. For the present application it would be safe to assume that the coefficient of absorption does not change, while density of the coal-air mixture does.

Ohmart Corporation, Cincinnati, Ohio, makes Beta radiation density equipment which may be used to determine the density and hence the coal concentration in a given section of pipe. The equipment costs $3500 and includes source, special windows for pipe, and low voltage radiation cell (Ohmart Cell).[29]

Ohmart supplied this type of equipment to Georgia Power Company who was interested in using nuclear radiation absorption techniques and differential pressure measurement across a venturi section to measure coal flow and air flow rates in a pneumatic conveying system. Although the results of Georgia Power Company's work are unknown, the literature search showed that the flow velocities of coal and air are not equal. Thus, knowing concentration and total bulk flow rate does not determine the individual flow rates. However, the coal and air flow rates may differ by a constant factor (1/2 has been suggested) over a reasonable range of flow rates, in which case concentration and bulk flow rate could be used to determine individual rates.

Industrial Nucleonics[18] also makes a radiation density device. Accu-Ray uses gamma radiation and does not require special windows in the pipeline, although shielding is heavier on the source and other equipment. The price is also $3500 and the basic equipment setup is similar to Ohmart's.

Both equipment manufacturers advertise their gauges for use on pipes up to 14 inches. Industrial Nucleonics has a special model for up to 24 inch pipes, although for larger vessels or pipes they recommend measuring across a cord. The reason for this is evident from the above equation on transmittance; a doubling of the pipe diameter requires a 6.7 fold increase in source level to maintain radiation level constant at the detector. For this reason, it might be better to use backscattering techniques as described below for large process pipe applications. This technique would lead to both a smaller radioactive source and shielding requirement.

Sun Oil Company[25] is using gamma radiation in an unconventional way. When gamma photons are directed into any substance, a certain percentage are scattered back toward the source at a reduced energy level, in an amount proportional to the density of the substance but independent of the composition. Sun has put this principle into use with an instrument designed and built by Densitronics Inc., Columbus, Ohio. The device consists of a 6½ lb. handheld probe containing a shielded gamma source (cesium-137) and a backscatter detector. An additional 4½ lb. instrument pack contains auxiliaries.

The company's use of the backscatter technique offers a number of advantages over the conventional techniques described above: (1) density can be determined simply by holding the calibrated device against a vessel wall, (2) vessel or pipe diameter is not a limiting factor, (3) radiation is low, therefore shielding requirements are also low, and (4) one man can make the measurements. The company has had great success with backscattering for finding liquid levels (i.e., abrupt change in density) in reactors, accumulators, and fractionators with metal wall thicknesses as great as 7/8 in. The device has also operated successfully on equipment with metal walls up to ½ in. thick plus two inches of insulation.

Nuclear-Chicago Corporation[28] also makes a backscatter device, which is similar to the Densitronics handheld unit but weighs 35 lb. The Nuclear-Chicago density gauge comes in two models: one for measuring asphalt density on a road surface, the other for density and moisture determination of compacted soils. The moisture density gauge uses a radium-beryllium source that emits both neutrons (for moisture determination) and gamma rays. It might be possible to adapt one of these models to density measurement in a pipe, although the low density of the coal-air mixture would not require as strong a gamma ray source.