EVALUATION OF A COANDA NOZZLE
FOR PNEUMATIC CONVEYING

By

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FOR PNEUMATIC CONVEYING

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TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Background Information

For many years, pneumatic conveying has been an acceptable method for the conveying of particulate material. Some of the reasons for its popularity are the ease of linkage to other systems, the total enclosure of the system and the economy of such an installation.

In recent years, the pneumatic conveyor has been used to mechanize the feed handling for confinement feeding operations. With this system, the operator has a fully mechanized feeding system with little manual labor and the elimination of feeding trucks and wagons. The conveying system empties itself in a matter of seconds which permits rapid changes in rations. Conveying systems constructed with augers and drag chains have considerable time delay and thus do not empty rapidly.

The most popular type of pneumatic conveyor uses a high velocity air stream to carry the particles through the pipe. The minimum air velocity required to transport feed grain over 100 feet is approximately 3,500 feet per minute. The pressure available to the system is the limiting factor for the conveying distance (3).

Material may be introduced into a pneumatic conveying system by many different methods. The type of feeding device depends upon whether the system is a low or high pressure system. A system that has a low or negative pressure can use a column-type injector or gravity feed system on free flowing material. A disadvantage of this system is the lack of material flow regulation. For systems under higher pressures a venturi can be used. Other types of material feeding devices are the star-wheel air-lock and the auger with a plugging chamber, which are quite expensive. This study is an attempt to construct a pneumatic conveying system that will allow a positive and inexpensive method of material injection.

The Coanda effect causes a tendency for a fluid to adhere to walls or to be deflected by a boundary in its path. This effect may be demonstrated by pouring liquid from a bottle and watching the curvature of the stream around the lip of the bottle. Henri Coanda describes this effect in a 1932 French patent. The turning caused by the boundary between the fluid and the wall allows momentum and flow augmentation. An internal nozzle has been made that uses this Coanda effect.

The fundamental features of the Coanda nozzle are shown in Figure 1. The primary air flow enters the reservoir from outside sources and then leaves the chamber through a slot which causes a high velocity air stream. This high velocity air entrains large quantities of ambient air in the nozzle. The fluid that is entrained near the deflection surface, which is called the secondary air stream, is accelerated causing a reduction in the static pressure on the surface. The lower pressure causes the jet stream to deflect toward the lower pressure and as a result, the jet stream is able to turn through a large angle and follow the deflecting surface.

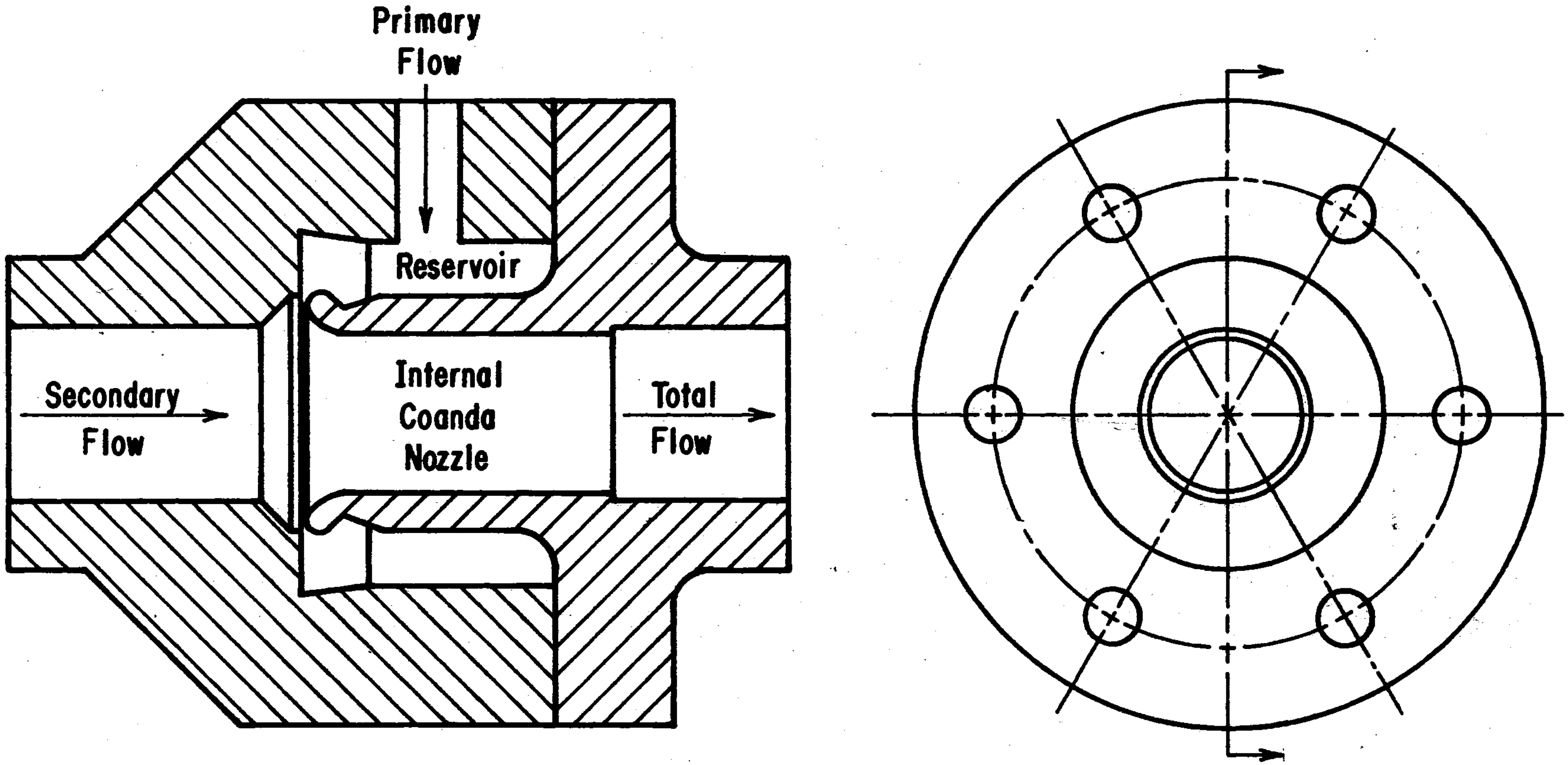

Figure 1. Internal Coanda Nozzle

The use of the Coanda nozzle as the air injector allows the conveyed material to be fed into the secondary air stream which is a negative pressure area. After the nozzle, the conveyor has the characteristic of a medium pressure-low volume conveying system.

The above discussion is presented in the following formal objectives.

Objectives

A. To construct and evaluate the performance of a Coanda nozzle system for the pneumatic conveying of granular agricultural products.

B. To determine the effect of the secondary air flow rate on the material conveying characteristics of the system.

C. To determine the effect of the material flow rate, introduced into the secondary air stream, on the material conveying characteristics of the system.

CHAPTER II

REVIEW OF LITERATURE

Conventional Pneumatic Conveyors

Pneumatic conveying is the transport of granular material through a closed pipe system. The conveying is accomplished by the introduction of air into this closed system. These systems are becoming more popular because of economy, mechanical simplicity, ease of path design and construction, and its adaptability to equipment already in use. Two disadvantages are possible damage to the conveyed material and the high power requirement to overcome energy losses from the air alone (2).

Pneumatic conveying systems can be grouped into three general classes: negative pressure, low or medium pressure and high pressure. The negative pressure system has below atmospheric pressures. The pressure differential has a maximum of two-thirds atmospheric pressure which results in a high air to material ratio and limits the conveying distance (1). Negative pressure conveying systems produce a minimum of material damage and a dust free atmosphere in case of leaks.

The second class, low or medium pressure, has two subclasses. Low pressure-high volume conveying usually uses an impeller or centrifugal type blower. A pressure up to 14 inches of water is obtained with the system. The material is generally fed into the system through the blower which may damage the material. The other sub-class, medium pressure-low volume conveying, uses some kind of positive displacement blower to obtain approximately 20 psi conveying pressure. This system allows the use of small diameter pipes. The air velocity for both types of conveyors in the second classification is approximately 3,500 feet per minute. The smallest pipe size should be selected that will handle the material flow at the given pressure.

The third class of pneumatic conveying is the high pressure-low volume system. This is often called a fluidized system. The pressure exceeds 20 psi for this system. The material should behave as a fluid and will be conveyed as a fluid (2,3).

A successful medium pressure-low volume pneumatic conveying system, developed by H. B. Puckett at the University of Illinois, has been in operation since 1958. This system is designed to handle the feed preparation and distribution portion of a hog finishing operation. A second system was installed on a turkey farm. The system has a capacity to handle approximately 30,000 turkeys (3,8).

Puckett has done extensive studies on these conveying systems and similar systems. The conveying system uses a one-inch conveying pipe. The typical feed flow rate is 1200 pounds of feed per hour, at 7-1/4 psi, which gives a maximum conveying distance of about 400 feet. The air flow to convey this capacity is about 25 CFM (8).

Material-Feeding Devices

The type of material feeder is dependent largely on the operating pressure of the conveyor. One method of setting particles in motion in a pneumatic conveyor is to inject air into the material hopper. Another way to convey particulate material is to inject this material into an already moving air stream. For this study the latter type of feeding device will be considered.

Positive pressure systems use the simplest type of material feeder, the gravity flow feeder, and usually with the aid of a venturi. This venturi lowers the pressure of the air stream to below atmospheric pressure at the point of material introduction, which aids in the prevention of blow back through the feed hopper. The venturi also adds to the cost of the system. Another disadvantage of this system is that it is not a positive metering device (1).

Another popular type of feeding mechanism is the rotary air lock. This system uses gravity flow to the rotor. The material drops into the compartments of the rotor, whose dividers provide an air seal and a positive metering mechanism. When the material is brought around to the outlet, the material drops again into the air stream. If a feeding device like this is used it is one of the major costs of a small pneumatic conveying system. The cost of a rotary air lock is between $300 and $1000 for a 1-1/2 inch dia. pipe system (4).

Augers are used as metering devices for many conveying systems. However, they have trouble holding an air seal when the auger is not injecting material into the system. Puckett (4) made an auger metering device with a flared plugging chamber that provided an adequate air seal. The injector used a 2-1/2 inch auger and worked under a pressure of 10 psi. It could inject up to 2000 pounds of material per hour into a one inch conveying line while turning 1800 RPM and had a power requirement of about 1.5 hp.

Negative pressure conveying systems can use the same types of feeders that are used by the positive pressure systems. If a gravity free flow feeder is used with the negative pressure systems, there is no need to use a venturi. The free flowing material will adjust itself to the demands of the conveyer. The rotary air-lock and the auger with plugging chamber injectors are not needed for negative pressure systems because the pressure seal is not needed; therefore, close tolerances are not essential.

Coanda Nozzle

According to Reba (6), Henri Coanda was one of the first to observe and describe the effect of a jet stream's tendency to adhere to and follow a surface that is in its path. Henri Coanda made several devices that utilized this effect. These devices are called Coanda nozzles. Two more common types of these nozzles are the internal and external nozzles. The internal nozzle (Figure 1) has the primary air chamber located around the nozzle opening. The external nozzle (Figure 2) has the primary air source located in the center of the nozzle with shrouding present to form the nozzle walls (5).

Victory (7) reported on a series of tests that were run on the Coanda nozzle. These tests evaluated the performance of the nozzle by analyzing the fluid thrust and momentum augmentation. The nozzle used in these tests had a 7.0 cm throat diameter and had a 66.8 cm divergent section following the nozzle itself. The slot opening was varied from .15 mm to .60 mm. The primary flow was regulated from about 32 cfm to 190 cfm at pressures ranging from 19.6 psi to 54.5 psi abs. Flow augmentation (exit flow/measured primary flow) of up to 16 was reached using the .15 mm slot opening. Thrust augmentation (measured thrust/primary momentum) of 1.25 was obtained using all slot

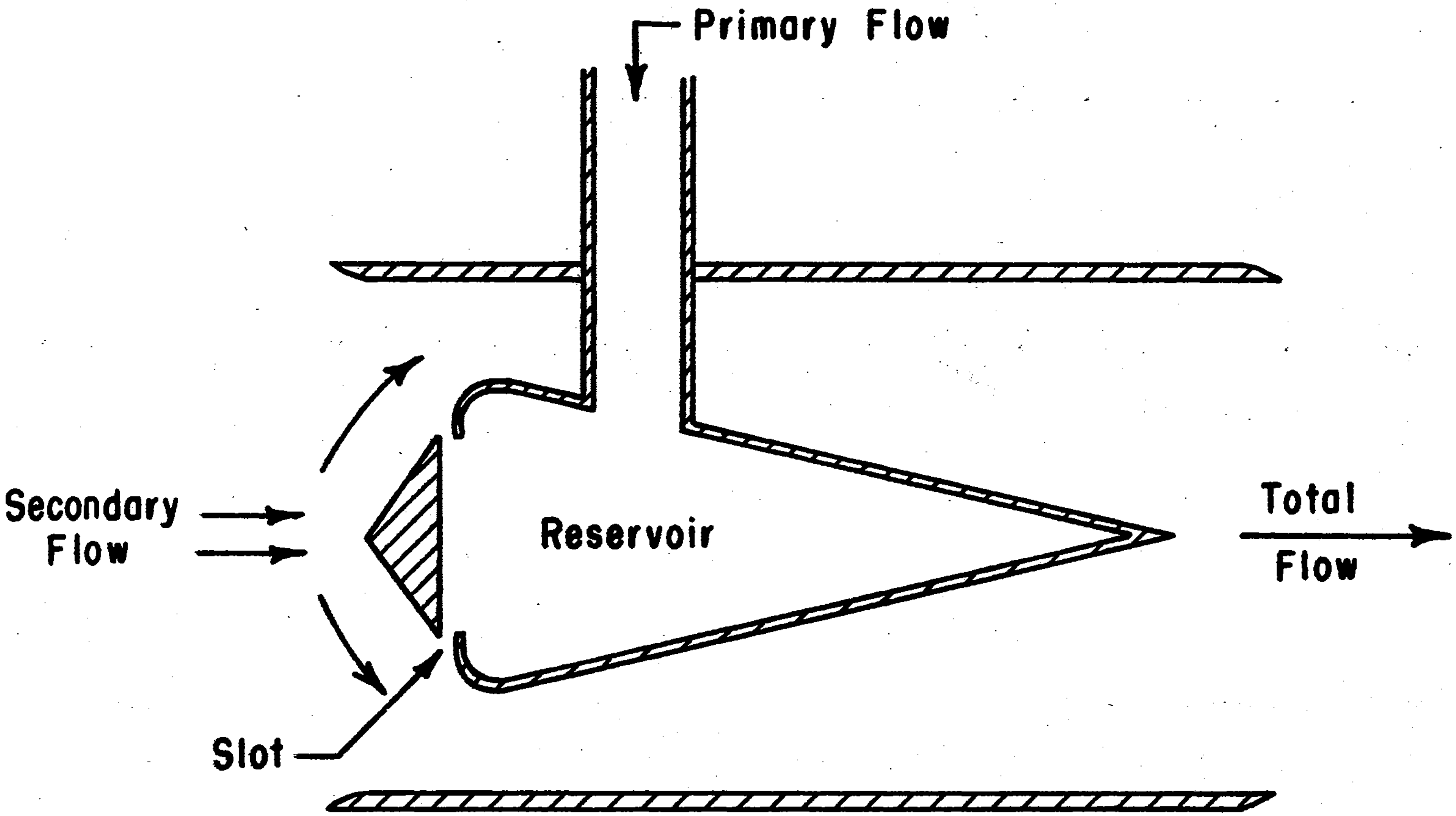

Figure 2. External Coanda Nozzle

openings. Momentum augmentation (exit momentum/primary momentum) of 1.71 was obtained also using all slot openings (7).

Experimental studies have been run on a Coanda nozzle by Reba, to determine the feasibility of mass transportation through use of the nozzle. In this series of tests, Reba used Coanda nozzles that had a 1-1/2 inch throat. The total system had a length of 78 feet with a nozzle at the entrance, one in the middle, and another two feet from the exit of the 1-1/2 inch diameter tube. The slot openings were varied from .002 inch to .010 inch. The primary flow was held constant for different slot openings resulting in different pressures. The flow was held at 25.74 cfm. Air flow augmentation up to 25.74 was recorded while testing nozzle performance. The static pressure across a nozzle was recorded as going from 0 to 36 inches of water. The pressure decreased to 20 inches of water in 33 feet of pipe. The velocity over this same length went from 135 feet/second to 143 feet/second. The conveyed material used was table tennis balls (2.5 gm), water-filled table tennis balls (30 gm), 3-inch long cylinders (8.3 gm) and 3 inch cylinders (165 gm), both with 1-1/2 inch diameters.

While using all three nozzles of the system, a velocity of 320 feet per second could be reached with the 2.5 gm table tennis ball, while the 165 gm cylinder only reached a velocity of 180 feet/second at the end of the system. The cylinder had not reached its terminal velocity because it was still accelerating when it had reached the end of the system (5).

CHAPTER III

DESIGN AND CONSTRUCTION OF THE SYSTEM

Several considerations were made before design parameters were established. A tube size and material was needed that would allow easy laboratory handling and construction. A one-inch aluminum conduit size was chosen so comparisons could be made with the systems researched by Puckett (34). The conduit size set the design characteristics for the rest of the system. Design of the Coanda nozzle was the first consideration in the construction of the conveying systems.

The Coanda Nozzle

With the conveying tube diameter set at one inch, a Coanda nozzle needed to be scaled down from a prototype discussed in the literature. Since the velocity of the jet stream depends largely on the slot width, it was believed an adequate velocity could be reached on a scaled down version of the Coanda nozzle.

A sectional view of the 70/84 nozzle, designed by Dr. Henri Coanda, was scaled down from a 7.0 cm throat to a one inch throat. The profile dimensions were taken graphically from a copy of the report from SFERI-Coanda (9). After the dimensions were taken and scaled down, drawings were made for fabrication by the Agricultural Engineering lab technicians.

The Coanda nozzle (Figure 3) was made of machined aluminum with

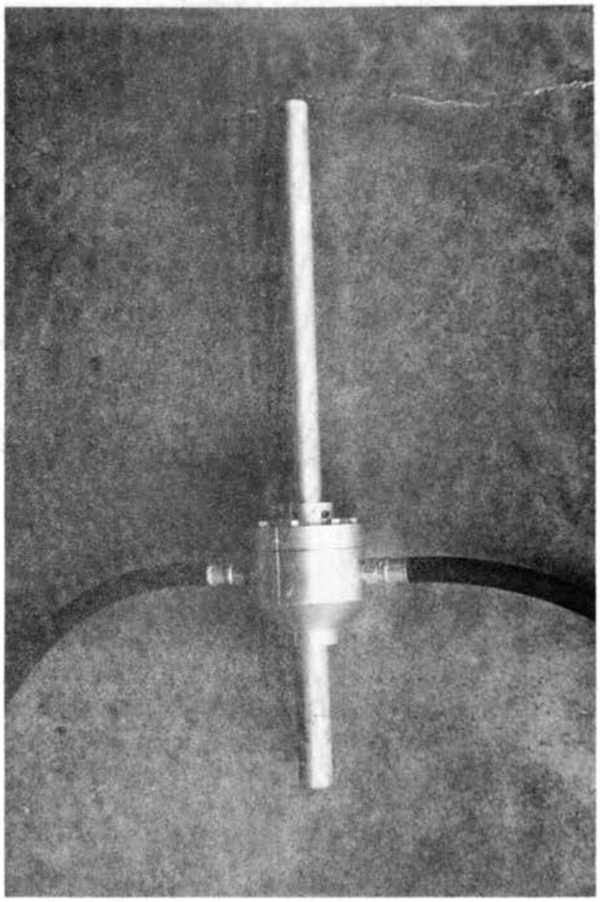

Figure 3. Coanda Nozzle

the complete nozzle in two sections. One section contains the Coanda surface (Appendix A-I and A-II), and the other section (Appendix A-III and A-IV) contains the wall that forms the slot between it and the Coanda surface. The slot width used shim stock spacers of .001, .002, .005, and .010 inch so that slot width could be varied in increments of .002 inch. The outside dimensions of the combined nozzle sections are 5 inches long x 4 inches in diameter. Both nozzle sections are machined to allow the conveying pipe to be slipped into place and fastened with set screws. The primary air enters the air reservoir through two separate ports 180° apart to provide for even air distribution around the nozzle's slot.

Material Feeding Device

An auger injection system was used because it was the simplest and most economical method available that would produce a regulated grain flow. A two inch downspout was used between the auger and the pneumatic conveying system. The pressure at the point of material injection was below atmospheric which eliminated the need for a pressure seal between the auger and pneumatic conveying pipe.

The hopper (Appendix A-V) was made of 16 gauge steel. Its volume was 4.5 cubic feet. The auger was 2.375 inches in diameter and had a pitch of 2.1875 inches, with a total length of 24 inches. A 3/4 inch pipe was used as the auger shaft. Grahm variable speed drive unit (Figure 4) with a speed range of 0-250 RPM was used to power the feeder. A number 40 chain drive having a 17:22 speed decrease was used for the drive. The downspout was made as a separate part from the auger tube (Appendix A-VI). A slide was located on the ambient air

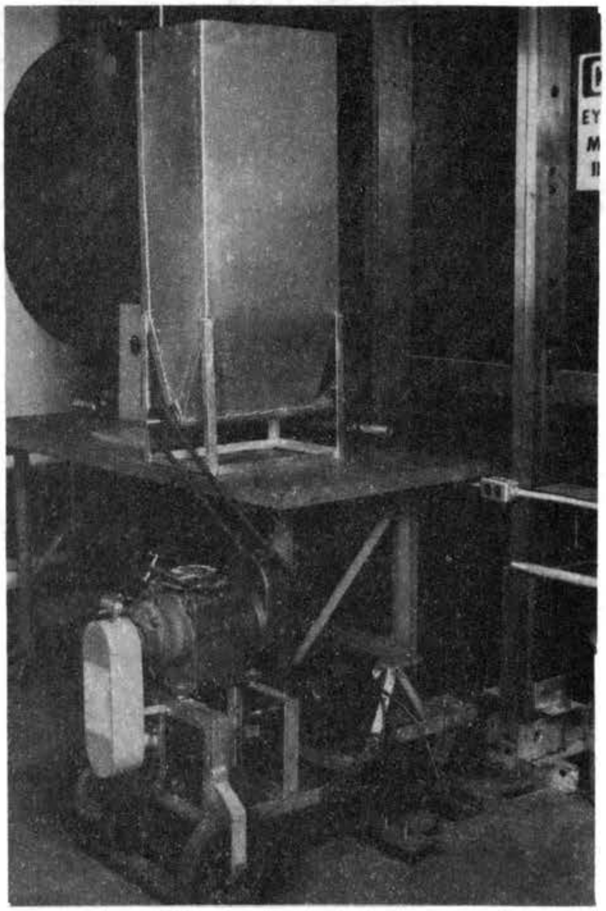

Figure 4. Grahm Variable Speed Drive
With Auger Grain Bin

side of the spout which could change the secondary air flow and velocity at the point of feed introduction into the system.

Since the conveying capacity of the pneumatic system was not known, the different feed rate settings were marked at the time of testing. These settings were later used to determine feeder discharge capacity with unobstructed flow. The calibration data is presented in Table I and is plotted in Figure 5. A third degree least-square polynomial equation was derived which had a standard estimate of error of .07364 or the largest percent difference from the original data was 3.75 percent.

While testing the nozzle with the feeder attached, it was discovered the bin must be sealed to eliminate air flow through the feeding system. Air movement through the feeder could not be monitored which would result in inaccurate secondary air flow readings. Therefore, a plastic cover was taped to the top of the feeder and all connecting joints were sealed with silicone rubber.

Pneumatic Control and Distribution System

The pneumatic control system (Figure 6) consisted of the primary air source, plumbing, controls, and monitoring devices. Also included in the control system was the secondary air tube and its velocity measurement device.

A Schramm 22 CFM-100 psi portable gasoline air compressor was used to supply the primary air flow for the conveying system. As the air left the compressor, it went through a 6 inch diameter by 24 inch water trap to help remove moisture from the air flow. An 11-002-74 Norgren pressure regulator was used to control the primary flow pressure. A number 10A1735X4 Fisher-Porter rotameter was used to measure air flow

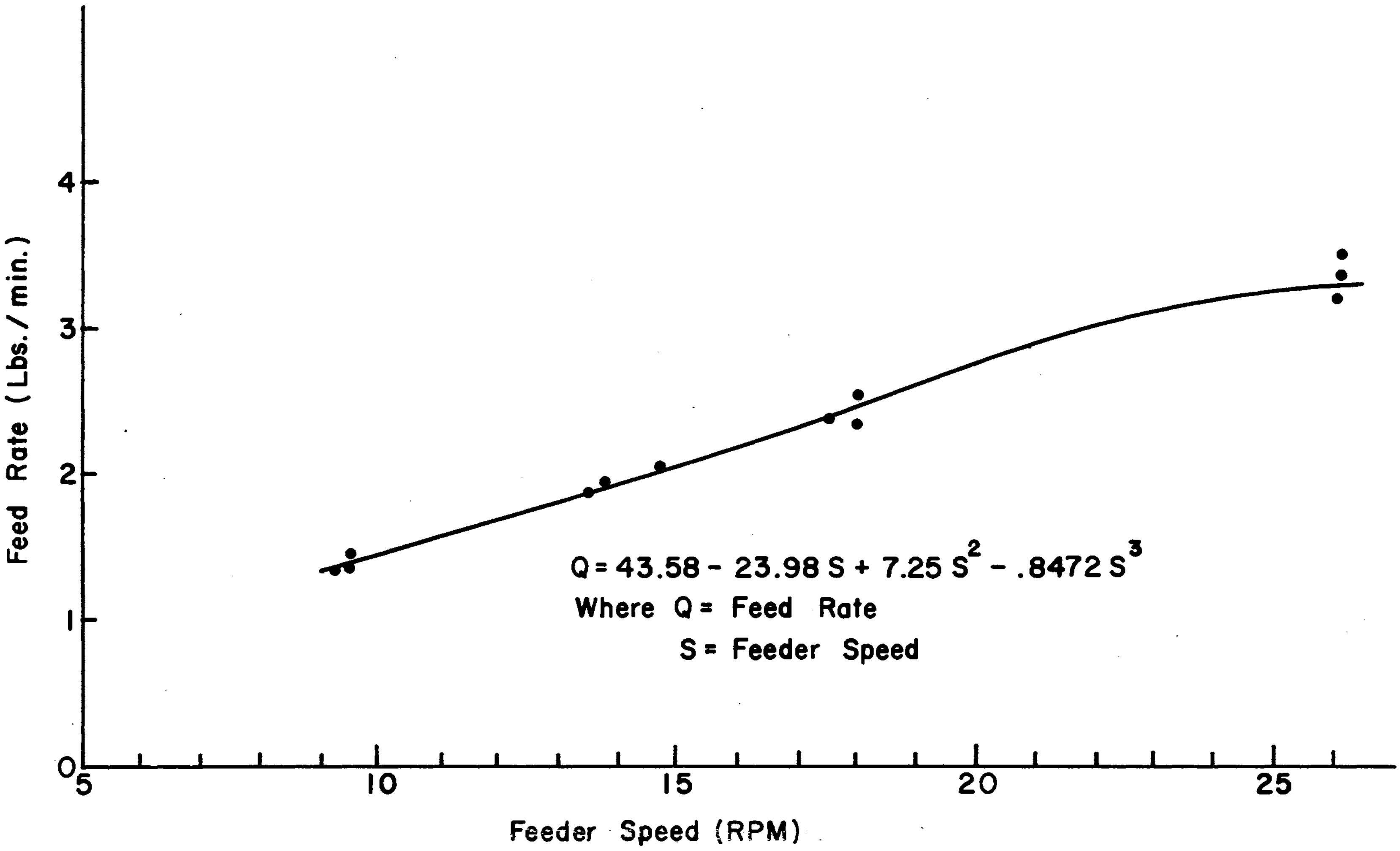

Figure 5. Feeder Calibration Curve

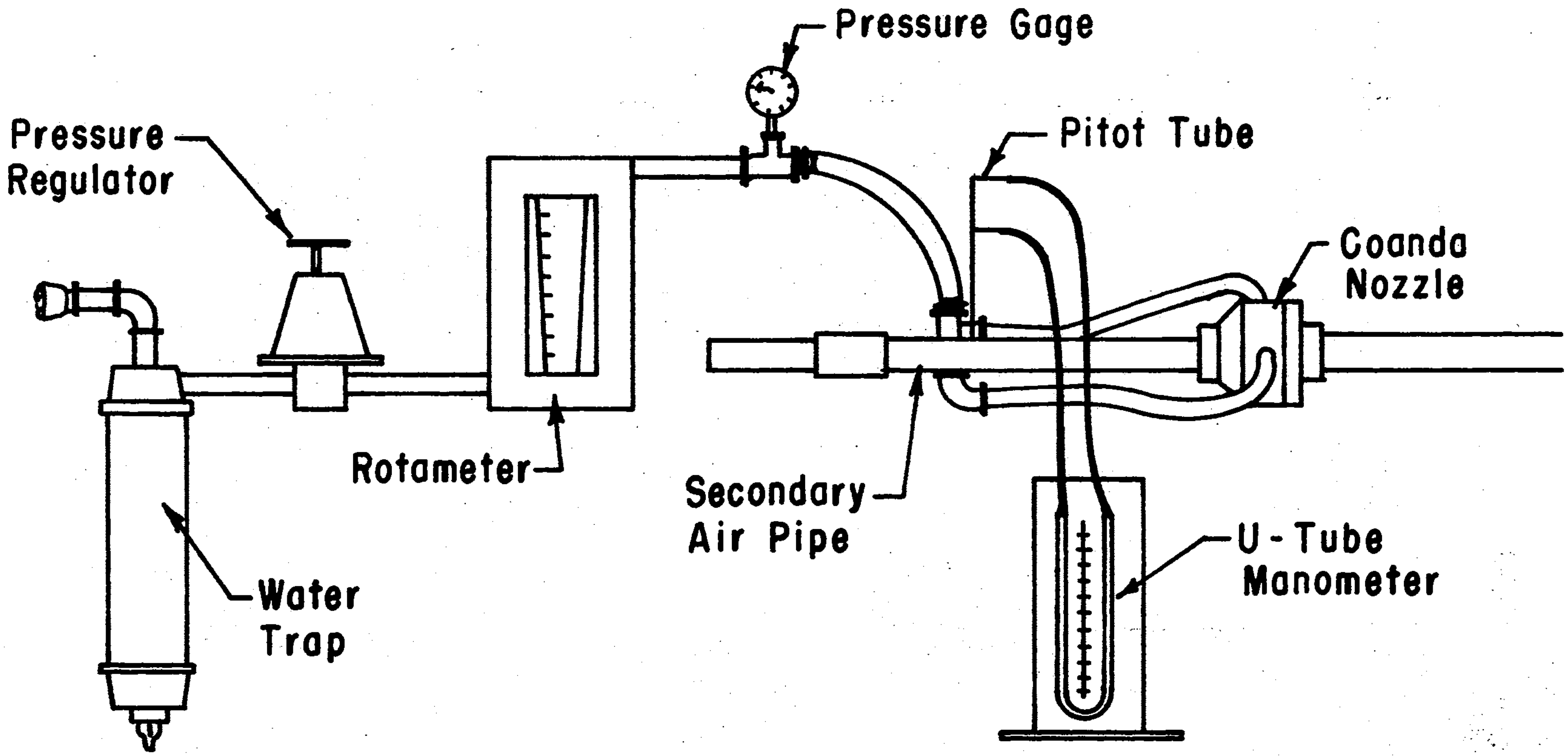

Figure 6. Pneumatic Control System

TABLE I

FEED RATE AND RPM CALIBRATION FOR THE MATERIAL FEEDING DEVICE

No. on Conveying Test	RPM	Feed Rate lb/hr
1	26	3.4
	26	3.32
	26	3.18
2	18	2.47
	17-1/2	2.34
	18	2.3
3	14-3/4	2.0
	13-3/4	1.88
	13-1/2	1.83
4	9-1/2	1.4
	9-1/2	1.32
	9-1/4	1.3

through the primary line. The approximate nozzle pressure was measured by a 200 psi pressure gauge mounted immediately after the rotameter. The 3/4 inch air line split from a tee into two 3/8 inch flexible, hydraulic hoses which were connected to the Coanda nozzle.

The secondary air path was directed through a one-inch electrical conduit that was 38-1/2 inches long. The actual inside diameter of the conduit was 1.040 inches. A 1/16 inch outside diameter pitot-static tube was located 20 inches from the secondary tube inlet. The pitot tube was connected to a 10 inch U-tube manometer to measure the secondary flow velocity head, which enabled the flow to be calculated. A 2-3/8 inches wide opening allowed the feeder downspout to clamp on the pipe which was 11 inches from the pitot tube and 4 inches from the nozzle.

The distribution system or the conveying pipe system (Figure 7) had a conveying pipe constructed of one inch electrical aluminum conduit with a true inside diameter of 1.040 inches. The pipe's 10 foot sections were connected with 4 inch pieces of 1-1/8 inch rubber tubing and clamped with 1-1/2 inch hose clamps. A static pressure reading was taken 32 inches downstream from the Coanda nozzle. A single copper tube perpendicular to the flow was used to take the static pressure reading. The tube was connected to a U-tube manometer, which had one side open to the atmosphere. This manometer was scaled to read inches of water using red oil, but in this case mercury was used as the manometer fluid. Another static pressure reading was taken 38 feet from the nozzle with a U-tube manometer. Forty feet from the nozzle, there were two nine inch elbows separated with a 20 inch pipe rise. Another static pressure reading was taken 14 feet from the last elbow with a 90 cm U-tube manometer. One foot from the pressure tap was a cyclone separater or dust collector with a double sacker downspout. The double sacker permitted samples to be obtained while the conveying system was running under steady state conditions.

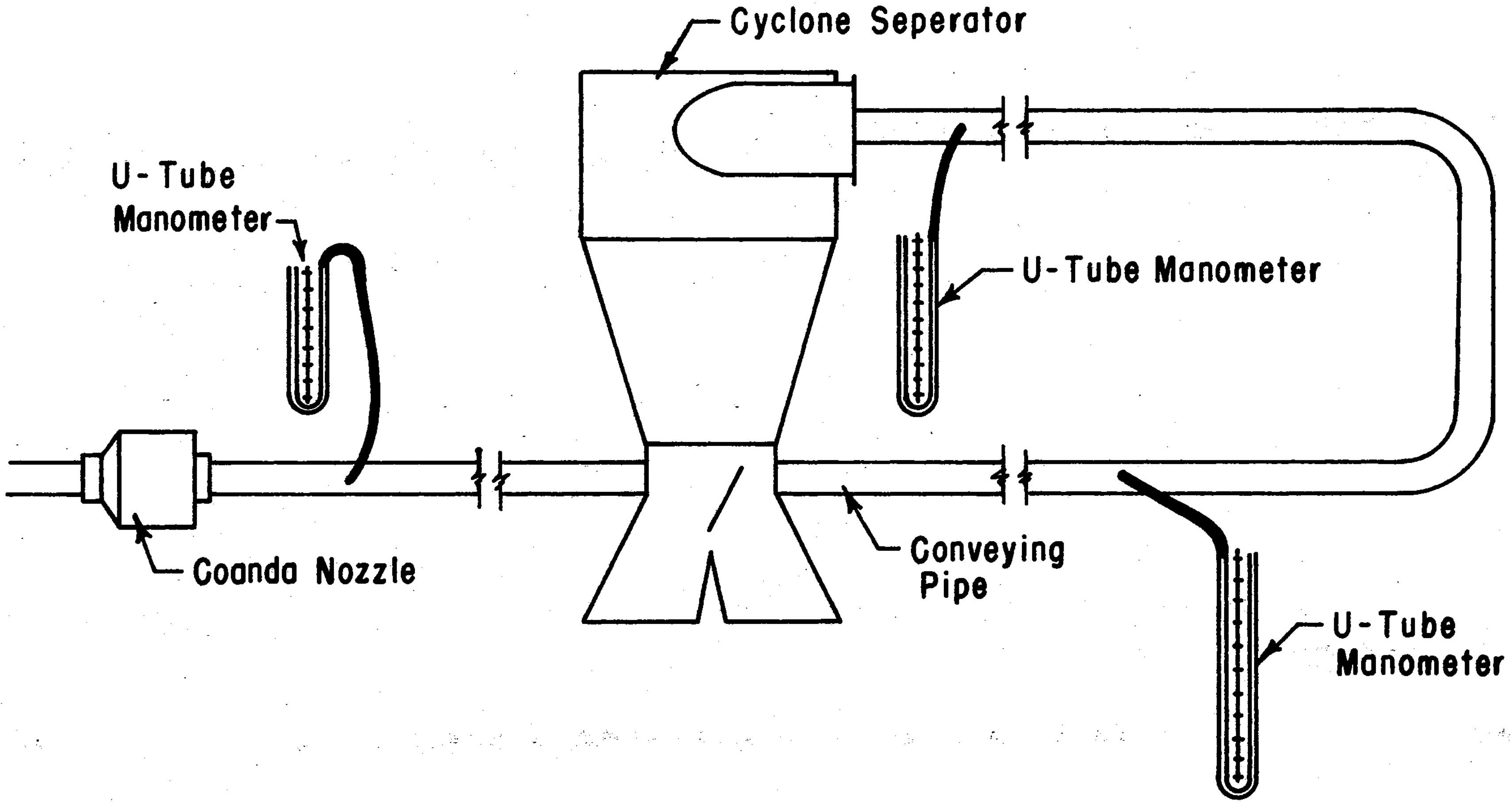

Figure 7. Pneumatic Conveyor Distribution System

CHAPTER IV

EXPERIMENTAL PROCEDURE

Calibration of the input flow measuring devices and experimental design are discussed in this chapter. Methods of obtaining the physical properties of the conveyed material are also shown in this chapter. Detailed procedures are given for testing the nozzle free air flow and material conveying capacities.

Rotameter Calibration

The rotameter was calibrated so that air flow rates could be calculated from the scale readings. The rotameter had a scale of a 0 to 1.5 etched on its glass tube. A 1/16 inch pitot-static probe was used to measure the velocity in the 3/4 inch pipe preceding the flow rotameter. The pitot tube was located in the middle of the 12 inch pipe. The velocity head of the air stream was read from a 10 inch manometer.

Velocity profile readings in the primary flow pipe were taken at a rotameter setting of 1.3 which was within the working range of the rotameter. The results of the velocity profile readings showed that the outer 1/3 area of the pipe had a pressure head of 1.95 inches of red oil (s.g. .827) while the inner 2/3 had a pressure head of 2.15. The average air velocity was 97.2 percent of the center velocity which was assumed to be constant for all rotameter readings in the working range (any reading above 1.0). There were very small variations between the two replications. The rotameter reading and the velocity head pressure were recorded as shown in Table II. The calculated velocities and air flows are also shown.

TABLE II

CALIBRATION OF ROTAMETER FLOW DATA

Air Density (lb/ft^3)	Rotameter Reading	Vol. Head Pressure (in. red oil)	Velocity (FPM)	Air Flow (CFM)
.0728	1.0	1.3	4215	15.362
	1.1	1.4	4374	15.937
	1.2	1.7	4820	17.566
	1.3	2.10	5357	19.524
	1.4	2.4	5727	20.872
	1.45	2.6	5961	21.725
.0732	1.0	1.3	4203	15.32
	1.1	1.4	4362	15.898
	1.2	1.75	4877	17.775
	1.3	2.2	5468	19.929
	1.4	2.4	5711	20.815
	1.45	2.6	5944	21.66

The primary air flow was then calculated using the CPS-360 IBM computer program in Appendix B-I. After the average velocities were calculated, a third degree least square polynomial equation was derived (Figure 8) from a public program called "POLFIT" in the CPS library. The equation had an index of determination of .995 with the largest calculated error of 1.88 percent.

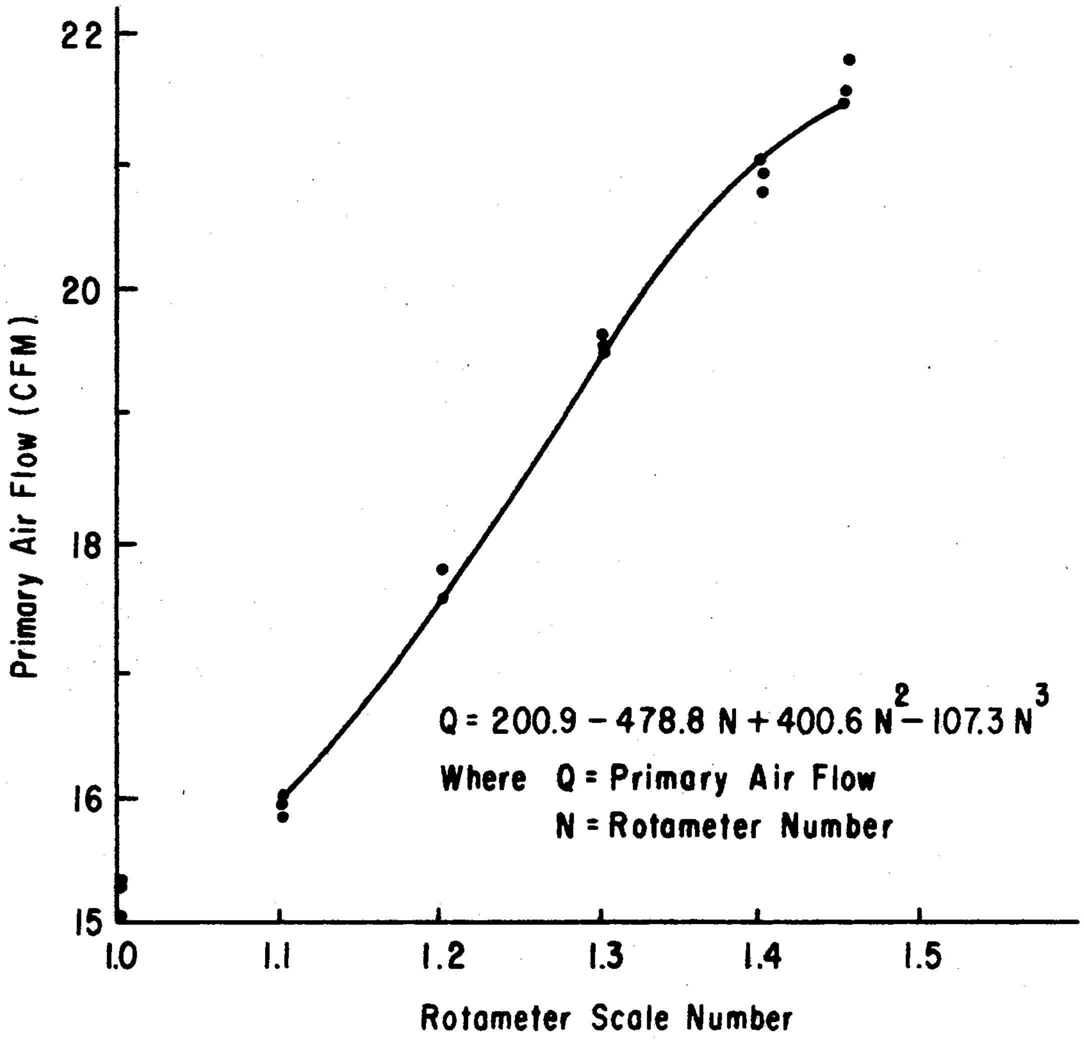

Figure 8. Rotameter Calibration Curve and Regression Equation

Secondary Air Flow Calibration

The secondary air flow was calculated from data taken from velocity head measurements. The readings were made on a 10 inch manometer connected to a 1/16 inch pitot static tube. The pitot tube was located 20 inches from the secondary air inlet. Since air flowing through a pipe has a velocity profile, it was necessary to calibrate or find the average velocity for a given center velocity. This would eliminate the need to take readings across the entire air stream and then integrate to obtain the average velocity for a given flow. The values are shown in Table III. Because of the small variation in data only two replications were run.

The average velocities were calculated for each flow by using the computer program shown in Appendix B-II. After the maximum and average velocities were calculated, a second degree least square polynomial equation was derived. A plot of maximum velocity vs average velocity is illustrated in Figure 9. The equation had an index of determination of .998 and the largest calculated error was 2.38 percent. This equation was later used to derive the average air velocity from the reading of the maximum velocity.

Free Air Measurement

Coanda nozzles of different sizes and design have different output characteristics. Since the nozzle was scaled down from a model 70/84 Coanda nozzle, the output characteristics would not be the same as previously tested nozzles. Therefore new nozzle characteristics had to be determined. All free air tests were run using a slot width of

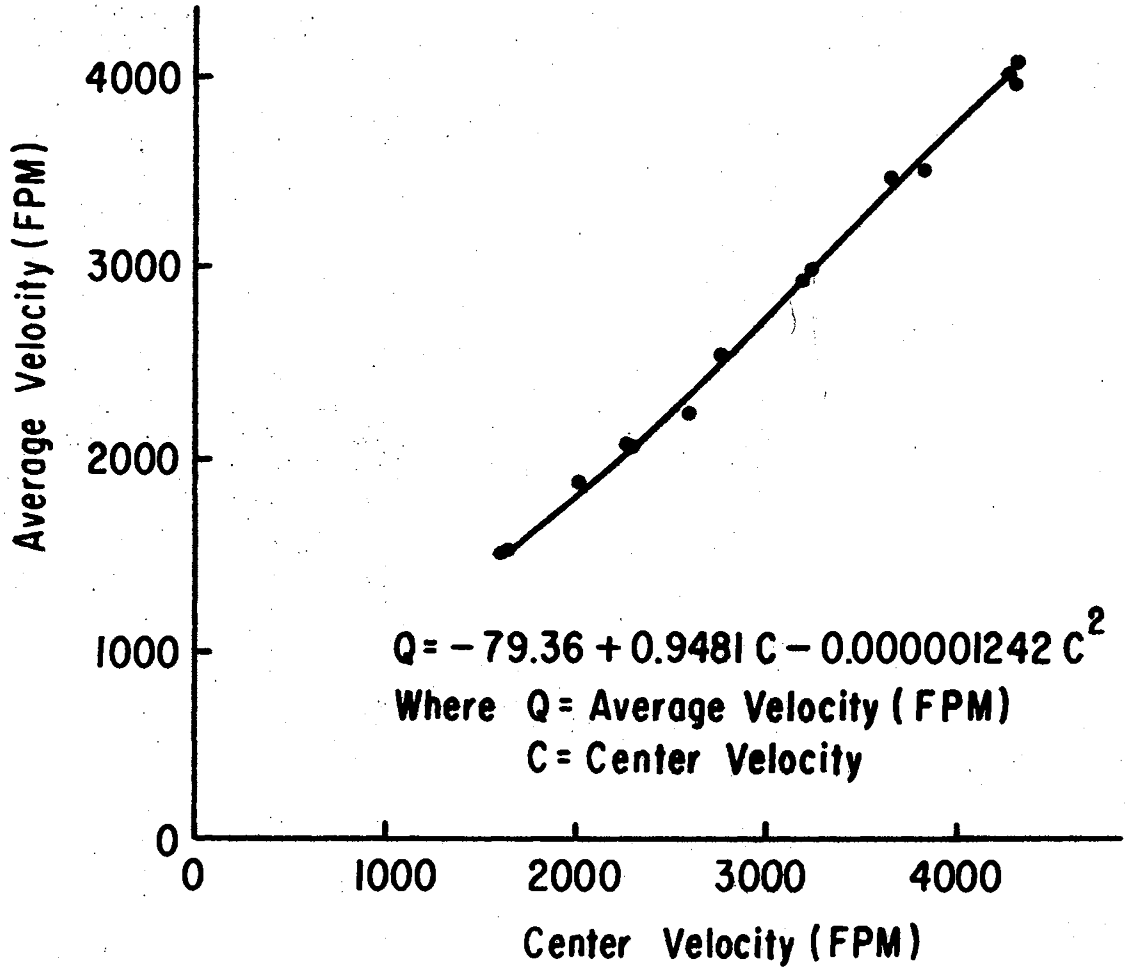

Figure 9. Average Air Flow Calibration Curve and Regression Equation

TABLE III

SECONDARY FLOW VELOCITY HEAD IN INCHES OF RED OIL

Rota-meter Reading	Slot Width	Air Density (lb/ft^3)	Pitot Tube Height From Bottom					
			1/64	5/64	9/64	7/32	11/32	33/64
.7	.008	.0712	.2	.25	.3	.35	.375	.375
.8			.275	.35	.4	.475	.5	.5
.9			.40	.5	.6	.7	.75	.75
1.0			.6	.8	.9	.95	1.05	1.05
1.1			.8	1.0	1.1	1.25	1.35	1.35
.8	.010	.071	.09	.15	.17	.19	.2	.2
.9			.16	.21	.26	.27	.3	.3
1.0			.35	.45	.47	.51	.55	.55
1.1			.65	.75	.85	.95	.95	.95
1.2			.75	1.05	1.25	1.35	1.35	1.35

.006 inch increasing to .020 inch in increments of .002 inch. The primary air flow was regulated by the pressure regulator and monitored on the flow rotameter. Tests were run with the rotameter reading above 1.0 (15.3 CFM) which helped to eliminate fluctuations in flow due to pressure variation. The tests were run with primary flow from 1.0 to 1.45 or until a maximum flow was reached. The slot width, barometric pressure, temperature, rotameter scale number, nozzle pressure, velocity head pressure and the conveying line pressure was recorded as shown in Appendix C-I. There were three replications run at each slot width. The range of nozzle slot width was selected from the air flow calculations obtained from the computer program shown in Appendix B-III.

The free air measurement procedure for the totally enclosed secondary air tube with 27 feet of conveying pipe was as follows:

1. Barometric pressure and conveyed air temperature were taken.
2. The Coanda nozzle was shimmed to obtain the selected slot width.
3. The air compressor was started and the pressure was allowed to stabilize.
4. The desired primary air flow was set with the pressure regulator.
5. Data was taken on the rotameter scale number, nozzle pressure, secondary velocity head, and the conveying line pressure 32 inches downstream from the nozzle.
6. Steps four and five were repeated until the complete rotameter scale was used.

The test procedure, when the grain bin was connected to the secondary air tube and 27 feet of conveying pipe was used, was the same as the previous six steps. The only difference was the apparatus setup. With this data (Appendix C-II), comparisons could be made for velocity loss due to any air leaks. The previous test results revealed the greatest secondary air velocities at slot widths of .010 inch and .012 inch. These slot widths were chosen because they showed the greatest secondary air flow velocities due to higher working pressures.

Particle Sizing

The grain sorghum that was to be conveyed had no fines in it. While sieving the grain with 8 inch Tyler sieves, it was found that three sieves were catching all the material; .132, .093 and .046 inch. Approximately one half pound of grain sorghum was put in the stack of three sieves and then hand shook for 40 seconds. Each sieve was emptied into its respective barrel and then the procedure was repeated. After the data was taken, calculations showed that 36.5 percent of the grain was retained on the .132 inch sieve, 60 percent was retained on the .093 inch sieve and the other 3.5 percent was retained on the .046 inch sieve. The weights and percentages are shown in Table IV.

TABLE IV

GRAIN SIZING TEST DATA

Sieve Opening Size (in.)	Grain and Can Weight (lb)	Can Weight (lb)	Grain Weight (lb)	Percent Retained
.132	38.25	19.5	18.75	36.5
.093	49.4	18.9	30.5	60.0
.046	22	19.25	2.75	3.5

Bulk Density Tests

The procedure for finding the bulk density of the grain sorghum was to take a direct reading of pounds per bushel from a one pint OHAUS measure and scale. There were three different samples taken. Then, the average bulk density, in pounds per bushel, was calculated from the data in Table V.

TABLE V

GRAIN BULK DENSITY TEST DATA

Sample Number	Bulk Weight (lb/bu)
1	58.7
2	58.0
3	59.1

Material Conveying Capacity

Before the conveying capacity tests were run, it was necessary to select a nozzle slot width that would best support pneumatic conveying. From previous tests, it appeared that small slot widths gave the optimum velocities.

The complete conveying apparatus was assembled. Tests were then run using slot widths of .010, .012, and .014 inch to establish which single slot width would be the best and to establish the friction losses in the conveying system due to air flow only. The complete rotameter scale above 1.0 was used on each slot width. Because of consistency in the results for all slot width data, only one test was run for each slot. Air flow calculations from the data in Appendix

C-III were made using the CPS-360 IBM computer program (Appendix B-IV).

The test procedure for free air flow measurement with complete system assembled is as follows:

1. Take barometric pressure and conveying air temperature after air flow has been established.
2. Shim Coanda nozzle to selected slot width.
3. Start air compressor and allow pressure to stabilize.
4. Set the desired primary air flow with the pressure regulator.
5. Data were taken on the rotameter scale number, nozzle pressure secondary velocity head, and static pressure readings at points 32 inches, 38 feet, and 57 feet downstream from the nozzle.
6. Steps four and five were repeated until the complete rotameter scale was used.

From the results of the free air tests, the decision was made to use a slot width of .012 inch. At this slot width the maximum primary air flow could be used and there was little variation in the secondary air flow. For the conveying tests, rotameter settings of 1.35 and 1.25 were used on the highest material flow rate and on all the lower material flow rates respectively. The material flow rates were 3.75, 2.4, 2.1 and 1.3 pounds per minute. The data obtained is shown in Appendix C-IV. Calculations of the primary air flow, secondary air velocity and flow, and total air flow were made by the CPS-360 IBM computer program shown in Appendix B-IV.

The procedure for testing the Coanda nozzle's material conveying capacity was as follows:

1. The barometric pressure reading and conveying air stream temperature were taken after the flow was established.
2. The air compressor was started allowing pressure to stabilize and then the primary air flow was set with the pressure regulator.
3. The secondary air stream slide was set to regulate secondary air flow.
4. The variable speed drive was set to the desired material flow rate, then the feeder was started.
5. Data were taken on the rotameter scale number, nozzle pressure, secondary velocity head, and the static pressure readings 32 inches, 38 feet and 57 feet downstream from the nozzle.
6. A 30 second sample of the material being conveyed was taken using the double sacker after the conveying system was in steady state.
7. Steps three through six were repeated until the four secondary flow openings were tested.

CHAPTER V

PRESENTATION AND ANALYSIS OF DATA

The first objective and the primary concern of this research was to determine the ability of a Coanda nozzle to convey particulate material. Data weretaken from the primary and secondary flow measuring devices along with the static pressure readings on the conveying pipe. Air flow and pressure calculations were made with the use of a computer program. A first degree polynomial line was fit to the test results to allow graphical representation.

Free Air Measurement

Nozzle Tests

The air density was needed for use in the secondary flow calculations and for corrections in the primary flow calculations. The air temperature and barometric pressure were the two variables needed for density calculations. The temperature of the conveying air stream was taken prior to any conveying. The air density equation in Marks (10), and shown below was used for the calculation.

$$D = (B - .38P)/RT$$

Where: D = Air density, lb/ft^3

B = Barometric pressure, in. Hg

P = Vapor pressure of water, in. Hg at 32°F

R = Constant, .7541 in. Hg

T = Absolute temperature, ^{o}R

The temperature and barometric pressure were observed and recorded. The vapor pressure for the temperature was obtained from Table I in Mark (10). Then the air density was calculated by a computer program shown in Appendix B-V.

The nozzle slot widths were varied from .006 inch to .020 inch, so that the best combination of slot width and primary air flow could be used for conveying. The primary air flow was regulated in a rotameter scale range of from 1.0 to 1.45 which was equivalent to 15.5 CFM to 22 CFM respectively. The nozzle was tested with 27 feet of conveying pipe attached.

There were three sets of tests run at each rotameter setting for all slot widths. The tests were run on different days which resulted in different air densities for the flow calculations.

At the smaller slot widths, the primary air flow was limited because a high nozzle pressure was required. The air compressor had an output of approximately 15 CFM at 50 psi which was the pressure requirement at the .006 inch slot width. If the nozzle pressure was low (under 9 psi), the air compressor would cut off and on which caused the primary flow to vary. Because of this, an average reading had to be made from the rotameter. When the primary air flow was started in nozzle widths greater than .012 inch, the secondary air passage had to be blocked to allow the Coanda effect to begin. If this was not done the primary air would exit through the secondary passage.

The computer program shown in Appendix B-III was written to make the nozzle's flow and pressure calculations from the raw data. Using a regression program, the following equations were calculated which were based upon the flow calculations obtained from the first program:

slot width (inch)	equation
.006	$y = 10.36 + 31.17x$
.008	$y = -1.685 + 37.97x$
.010	$y = 7.652 + 39.92x$
.012	$y = -8.395 + 37.22x$
.014	$y = -9.243 + 34.22x$
.016	$y = -3.983 + 27.62x$
.018	$y = -4.243 + 26.48x$
.020	$y = -2.449 + 23.34x$

where:

y = total air flow (CFM)

x = rotameter scale number

The regression program was called "POLFIT," a regression program in the conversational programing system (CPS) public library. The CPS terminal was linked to the IBM 360 computer at the Oklahoma State University Computer Center.

The "POLFIT" program calculated a percent difference, which was the actual data value of y minus the calculated value of y divided by the calculated value of y all multipled by one-hundred, for each value in the first order polynomial equations. The largest percent difference between the test data and the calculated value obtained from the above equations was five percent for only one of the values of y. Several differences of four percent were calculated but the average was about 1.5 percent. The equations were plotted on a single graph

(Figure 10) of rotameter scale number vs total flow so that the best slot width could be selected. The original data is given in Appendix C-I.

Nozzle Plus Bin Tests

Tests were run with the grain bin attached to the secondary air pipe. From the nozzle performance calculations, the .010 inch and .012 inch slot widths were the best for the desired output. These slot widths would permit a large primary flow and still provide a large secondary air augmentation. After these considerations were made, a single set of tests for each slot width was conducted with the grain bin attached. Calculations were made on the test results in the same manner as before. The following equations were plotted on the same graph (Figure 10) as the preceding data results:

slot width (inch)	equation
.010	$y = -11.06 + 38.85x$
.012	$y = -7.251 + 39.15x$

where:

y = total air flow (CFM)

x = rotameter scale number

The secondary flows with and without the grain bin attached were compared and the difference in flows was only three percent. With this small difference the system with the bin was assumed to be sealed or to have no leaks. The data for free air conveying with the grain bin attached is presented in Appendix C-II.

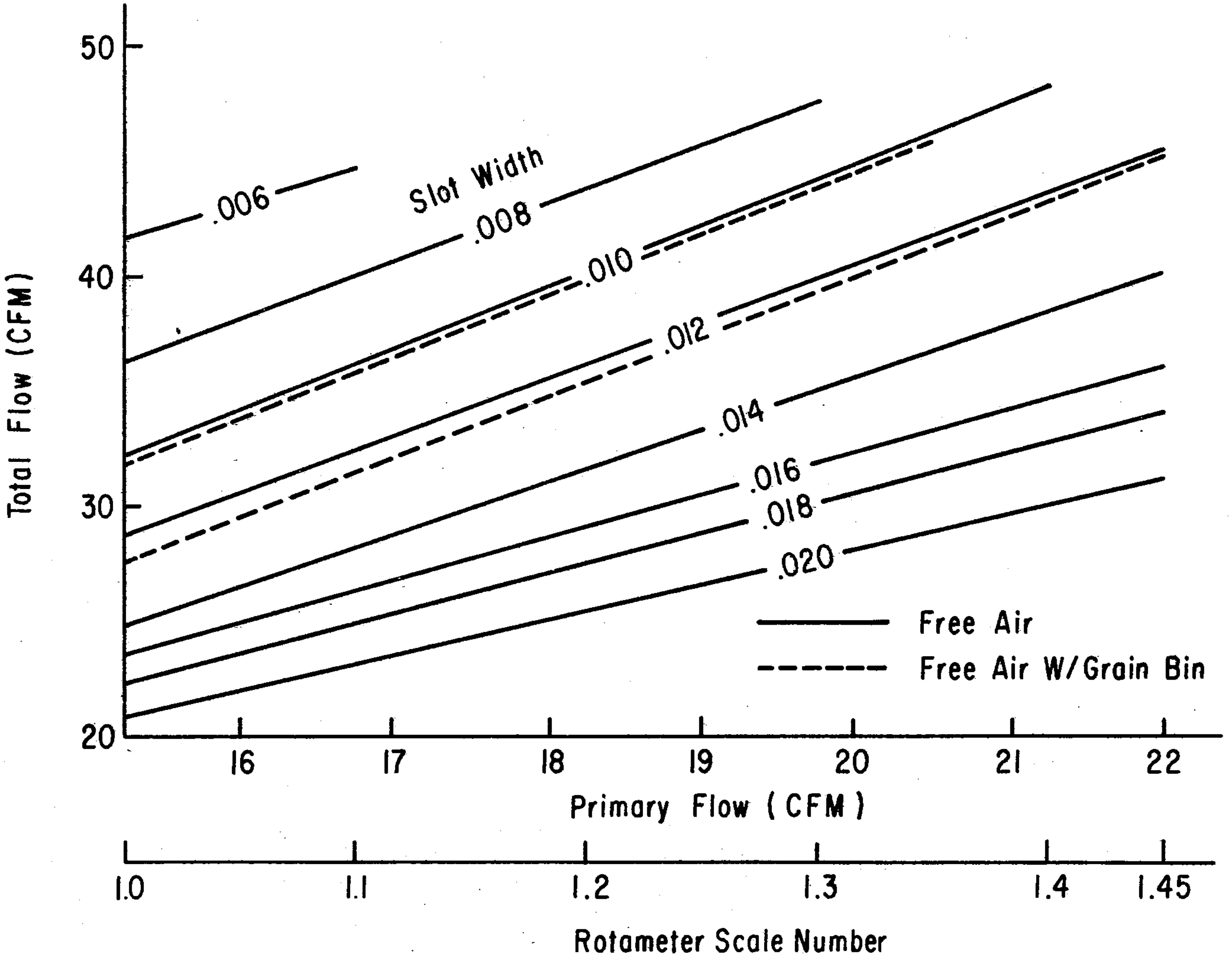

Figure 10. Coanda Nozzle Output Curves

Material Conveying Capacity

In order to finalize the decision of which slot size to use for conveying, three more groups of tests were run. The total apparatus was assembled and tests were run using the .010, .012 and .014 inch slot widths. The range above 1.0 on the rotameter was used for all tests. The input flow and pressure readings were recorded and the static pressure readings were taken. All data recorded in this set of tests was later compared to values obtained while the material was being conveyed.

A single set of tests were run for each nozzle slot width. Air flow and pressure calculations were made from the test data (Appendix C-III) by using the computer program in Appendix B-IV. The pressure loss and total flow calculation results were collectively put in the "POLFIT" regression program which resulted in the following equation.

$$y = -.8677 + .0508x$$

where:

y = pressure (psi)

x = total air flow (CFM)

The above equation was plotted (Figure 11) so the pressure loss vs total flow could be easily analyzed to find the pressure loss for the 38 foot section of conveying pipe due to air flow only. From the data in Appendix C-III it was found that the most desirable slot width was .012 inch. This slot width allowed the full primary flow to be used with only small differences in the secondary air flow.

Since the conveying capacity of the pneumatic system was unknown, a maximum value was found by trial and error. At the beginning of the

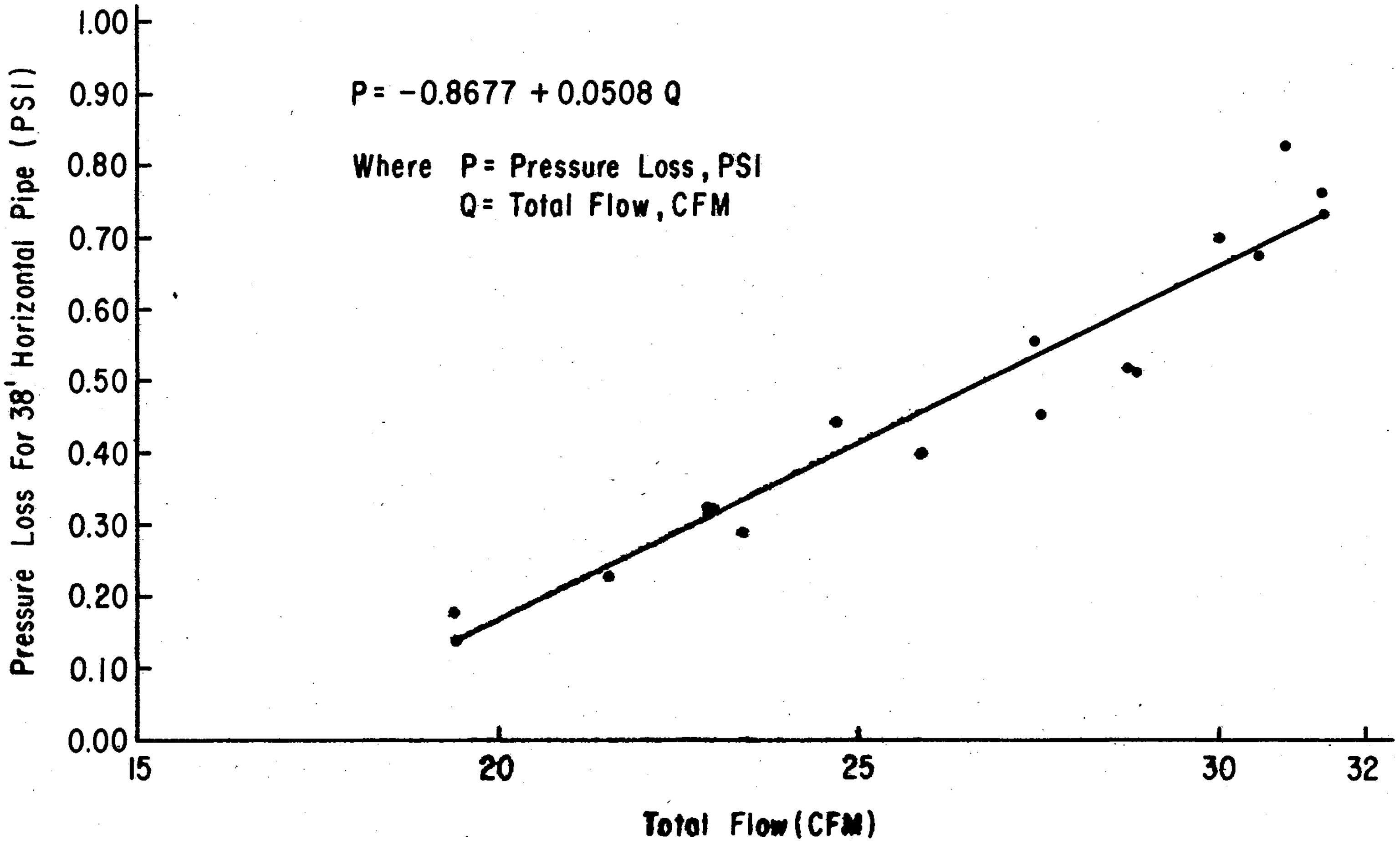

Figure 11. Coanda Nozzle, Total System, Free Air Output

test the primary air flow was set at its maximum value or about 22 CFM. The Grahm variable speed drive was increased in speed until the pneumatic conveyor would plug. The conveying capacity was increased by lowering the primary flow to 20.7 CFM. After the first material flow rate was marked on the variable speed drive (3.75 lb/min.) the speed was lowered to the next desired flow rate. Again it was found that a lower primary air flow (18.8 CFM) aided in the system conveying capacity. The air supply was left at 18.8 CFM for the remainder of the conveying tests. The Grahm variable speed drive was set for conveying capacities of 2.4, 2.1 and 1.3 pounds per minute for the other sets of tests.

Three sets of tests were run for each material flow rate. The secondary flow pipe was restricted with a slide on the grain bin downspout. The slide heights were 1/4, 1/2, 3/4 and 1 inch for each material flow rate. A test to determine the slide's effect on the secondary flow with free air was run. The primary air flow was 18.8 CFM while the slide was set at 1/4, 1/2, 3/4 and 1 inch. All secondary air flow readings were about 6.75 CFM which showed the slide had no effect on the free air system.

During the conveying tests, the material would surge through the pipe. This surging was apparently from the build-up of material in the secondary air pipe. When an air seal was formed by the grain, the suction from the nozzle would pull the grain into the nozzle. The grain build-up in the secondary flow pipe caused a large force in the auger and consequently the grain bin and variable speed drive had to be braced to overcome the large torque. When the auger was turned off, the grain would continue to flow in the conveying pipe for five to ten seconds.

Flow and pressure calculations were made on the data shown in Appendix C-IV with the computer program in Appendix B-IV. The pressure loss and feed rate data were then put in the regression program "POLFIT" which calculated the following equations:

feet rate (lb/min)	equation
3.75	$y = .5109 + 0069x$
2.4, 2.1, 1.3	$y = .3909 + .0148x$

where

y = pressure psi

x = feed rate lb/min

The largest calculated difference percent from these equations was eleven percent with the standard error of estimate being .020 psi for the smaller feed rates and seven percent difference with the standard error of estimate being .022 psi for the highest feed rate. The equations were plotted in Figure 12 with pressure loss vs feed rate to allow determination of pressure loss for a certain feed rate. Since the values of total air flow were known for the different feed rates (Appendix IV), values of pressure loss due to air flow only could be taken graphically from Figure 11. The total air flows for 1.3, 2.1, 2.4, and 3.75 lb/min. material flow rates were 23.8, 23.0, 22.6, and 23.9 CFM respectively. The pressure loss for air only in each case was .35, .32, .3 and .36 psi per 38 foot section. The free air pressure losses were plotted in Figure 12 under its corresponding feed rate-pressure loss curve. The difference between these curves were assumed to be the pressure loss due to the material conveyed.

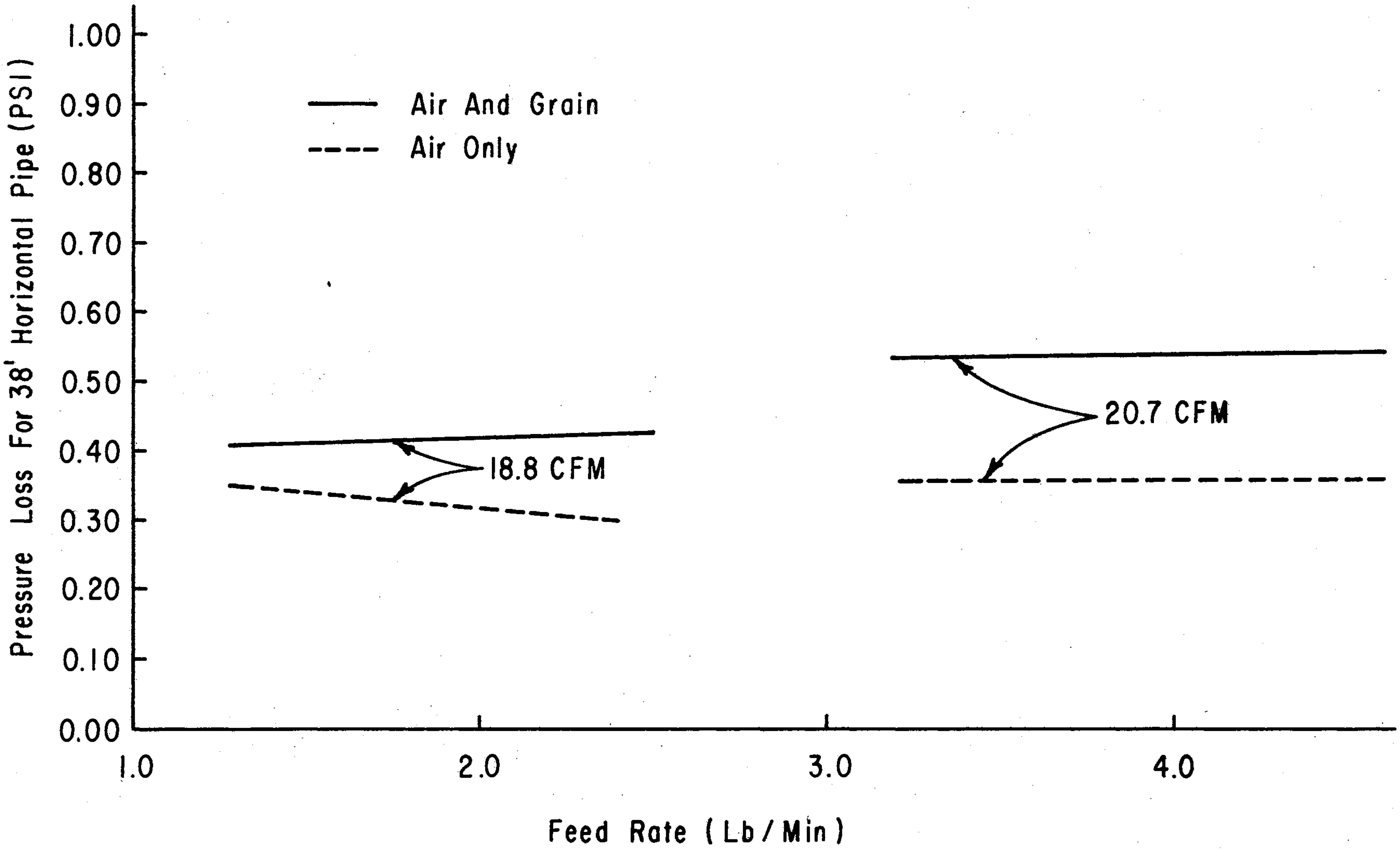

Figure 12. Pressure Loss for Conveying Rates

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

A pneumatic conveying system was designed and constructed with a Coanda nozzle as the device used for air introduction into the conveyor's pipe system. An auger injector was used to meter the grain sorghum that was to be conveyed. A one inch aluminum electrical conduit conveying pipe formed the path to the cyclone separator where test samples were taken.

Free air tests were run on the Coanda nozzle with varying primary air flow (15-22 CFM) and nozzle slot widths (.006- .020 inch). Based upon these tests a slot width and primary air flow combination was selected that would best support conveying of particulate material.

Final slot width selection was made after the total conveying system was fabricated and performance determined for three nozzle slot widths (.010, .012, and .014 inch).

The nozzle slot width of .012 inch was chosen for the conveying tests. A primary air flow of 20.7 CFM was used for the 3.75 pounds per minute conveying capacity and 18.8 CFM for the 2.4, 2.1, and 1.3 pounds per minute conveying capacity. The pressure loss for 38 feet of horizontal pipe was recorded while conveying.

A metal slide was used to restrict the secondary air pipe while conveying. The effect of the secondary air flow restriction was recorded.

Conclusions

The following conclusions are presented as a result of the work in this study:

1. The Coanda nozzle that was constructed had an adequate Coanda effect to cause a high velocity secondary flow.
2. When the 58 feet conveying pipe was linked with the nozzle, the greatly added pressure losses for the free air only caused the secondary flow to be lowered below the velocity requirements of pneumatic material conveying.
3. The maximum material flow rate was considerably lower than the capacities of other one inch pneumatic conveying systems reported in the literature.
4. The pressure losses while conveying grain sorghum for the 38 feet of horizontal pipe were 65 to 80 percent due to the air flow only, with the remainder due to the material.
5. The slide in the secondary air flow pipe had no apparent effect on the systems conveying capacity.

Suggestions for Future Work

1. A divergent section immediately following the nozzle which would connect the nozzle to a larger diameter conveying pipe should be tested for particulate conveying.
2. A shorter secondary pipe with the material introduction closer to the nozzle should be tested.

3. A method to allow a constant flow rate of material into the system should replace the present material injection system.
4. The possibility of conveying other agricultural products, such as peanuts, should be investigated.

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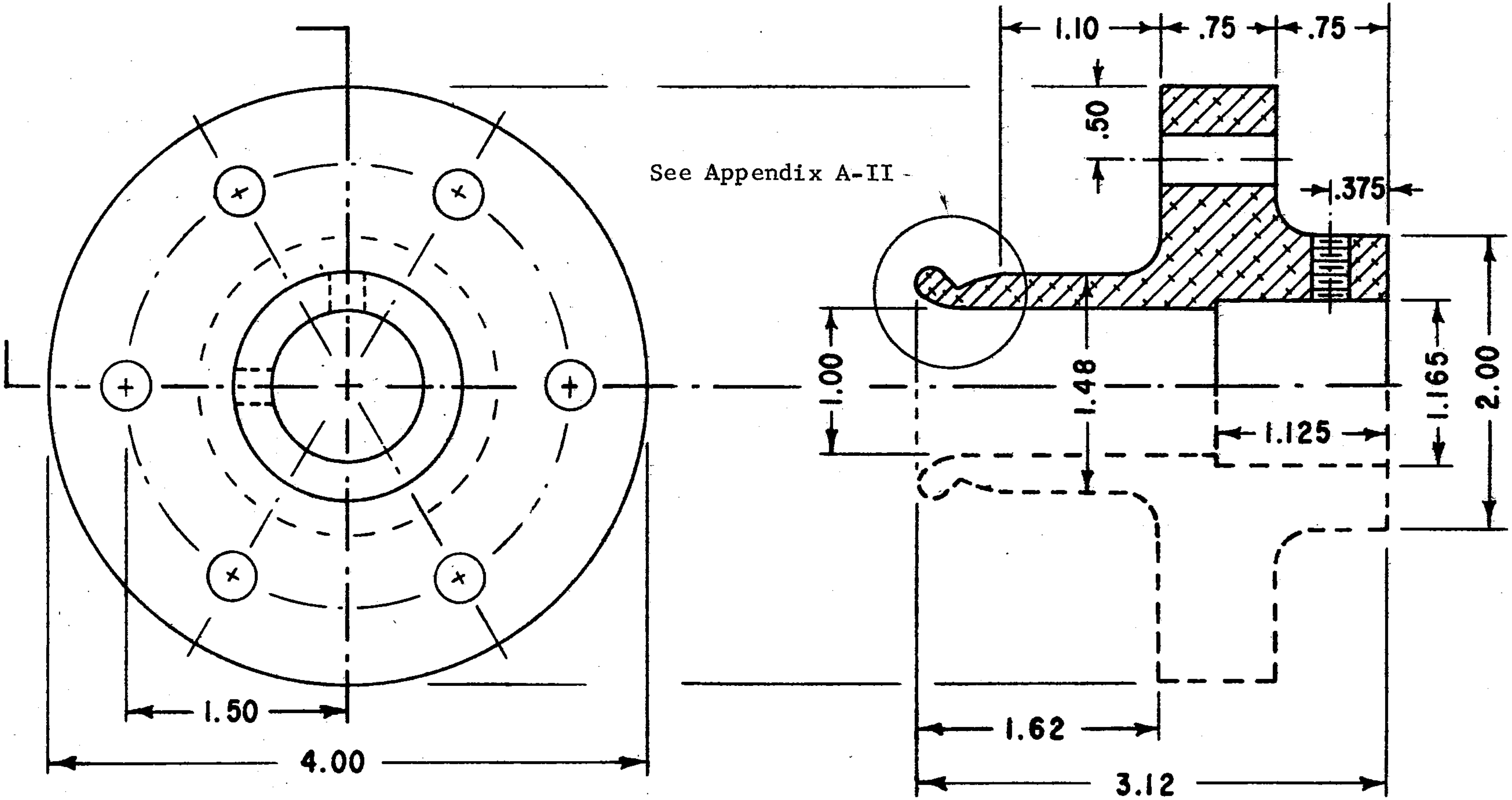
APPENDIX A

WORKING DRAWINGS OF
CONVEYING APPARATUS

APPENDIX A-I

COANDA NOZZLE SURFACE SECTION

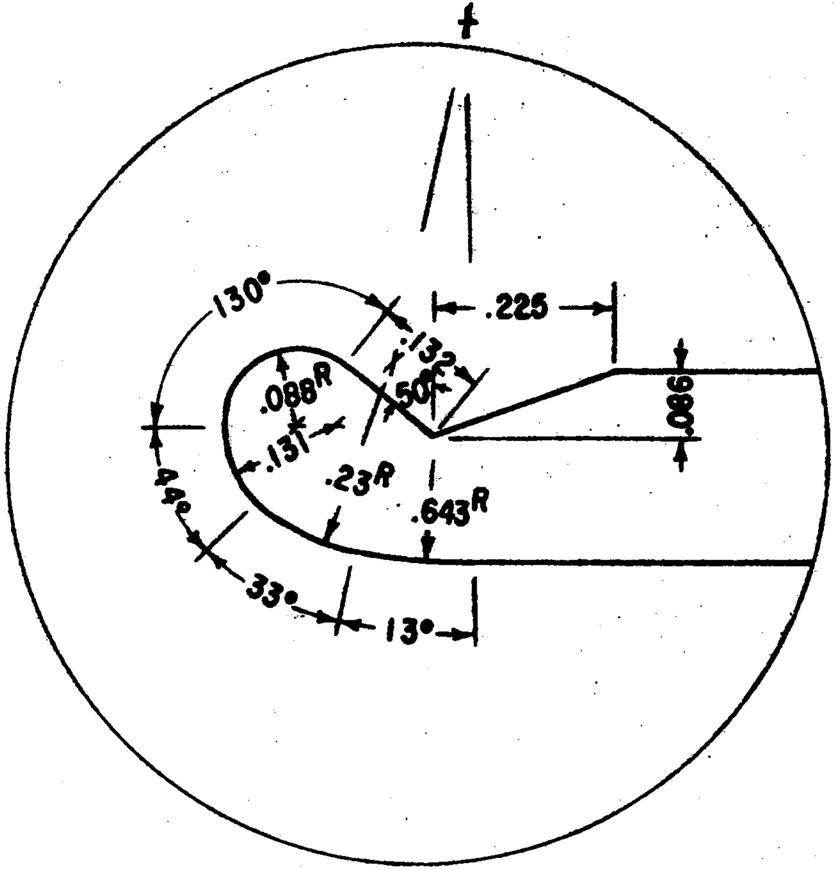


See Appendix A-II

Note: Drill 11/32 dia., 6 holes equispaced
Drill #7, Tap 1/4-20NC, 2 Holes
Material - 4" Dia x 3.12 Aluminum
Dimensions are in inches

APPENDIX A-II

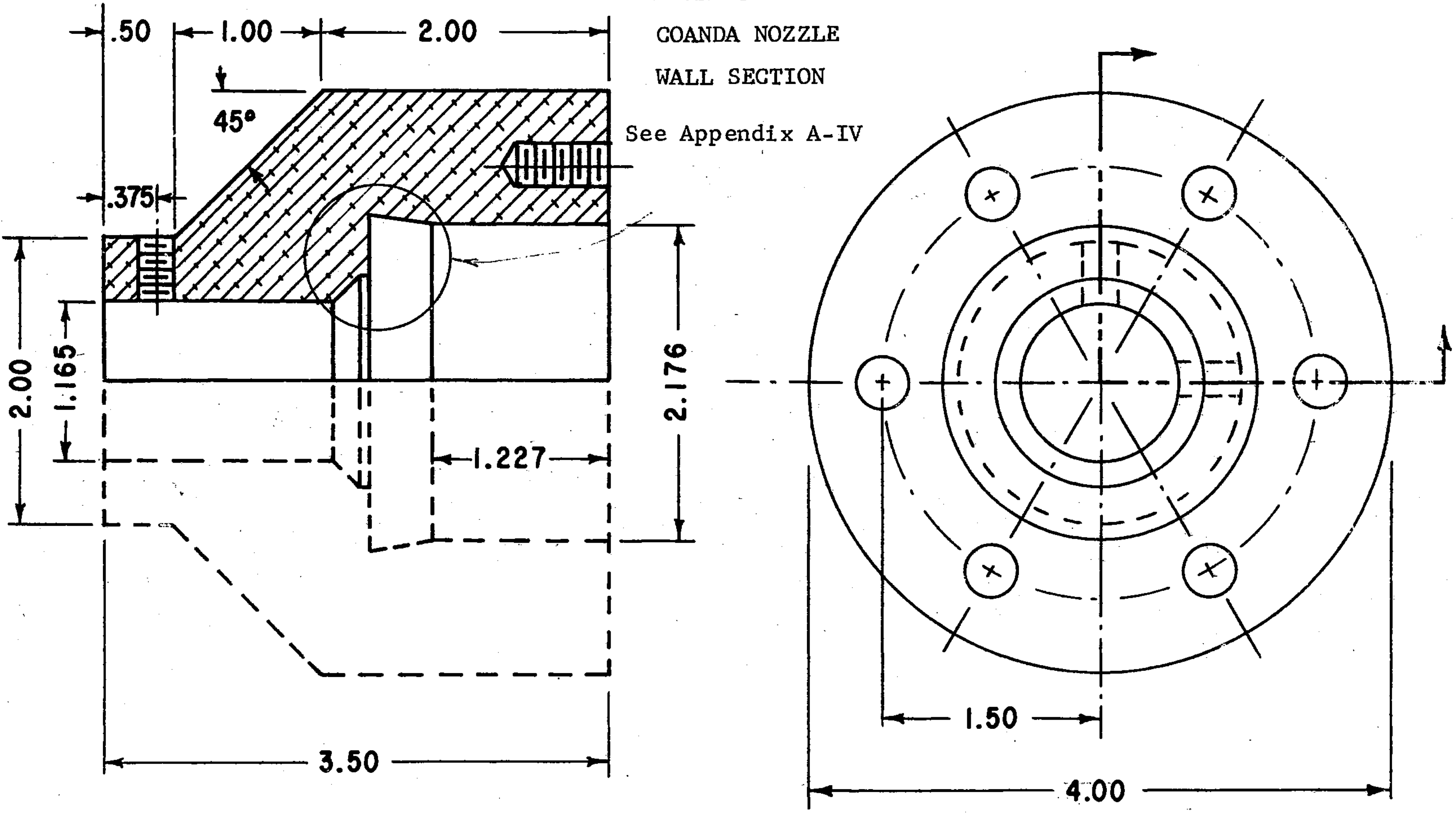
COANDA SURFACE DETAIL



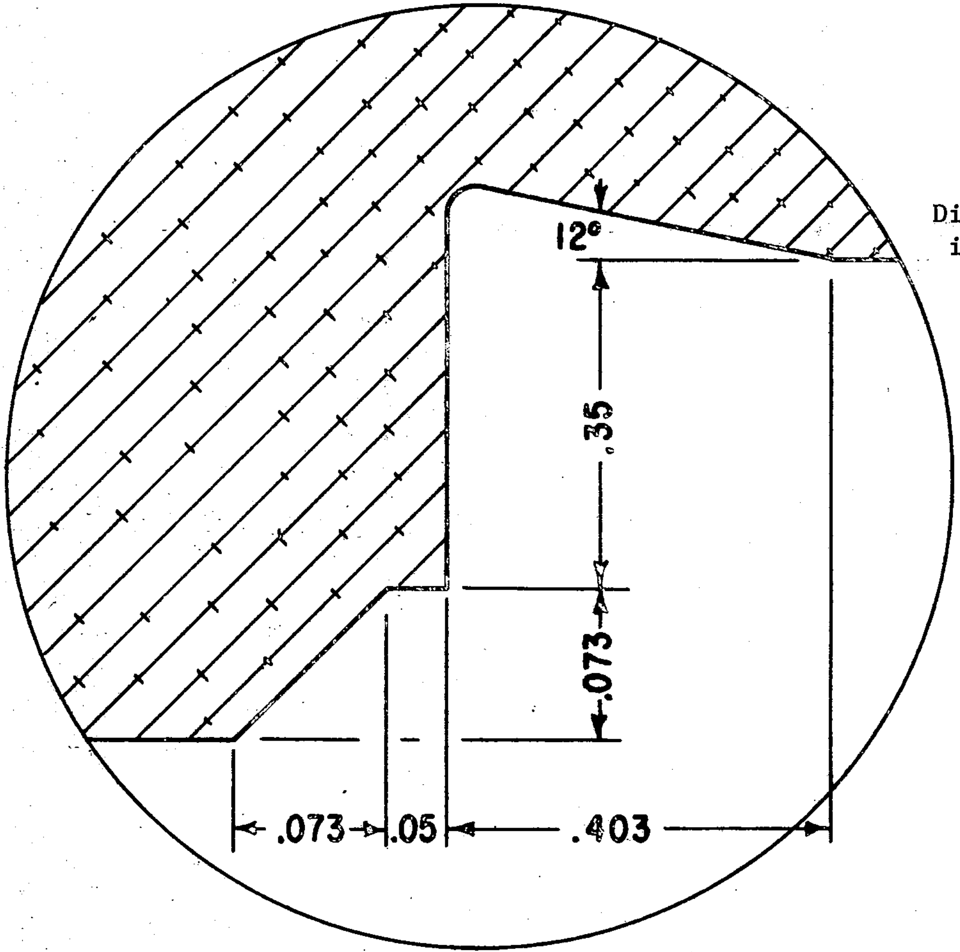
Radius Centers
are on Previous
Angle Lines

Dimensions are
in inches

APPENDIX A-III
COANDA NOZZLE
WALL SECTION



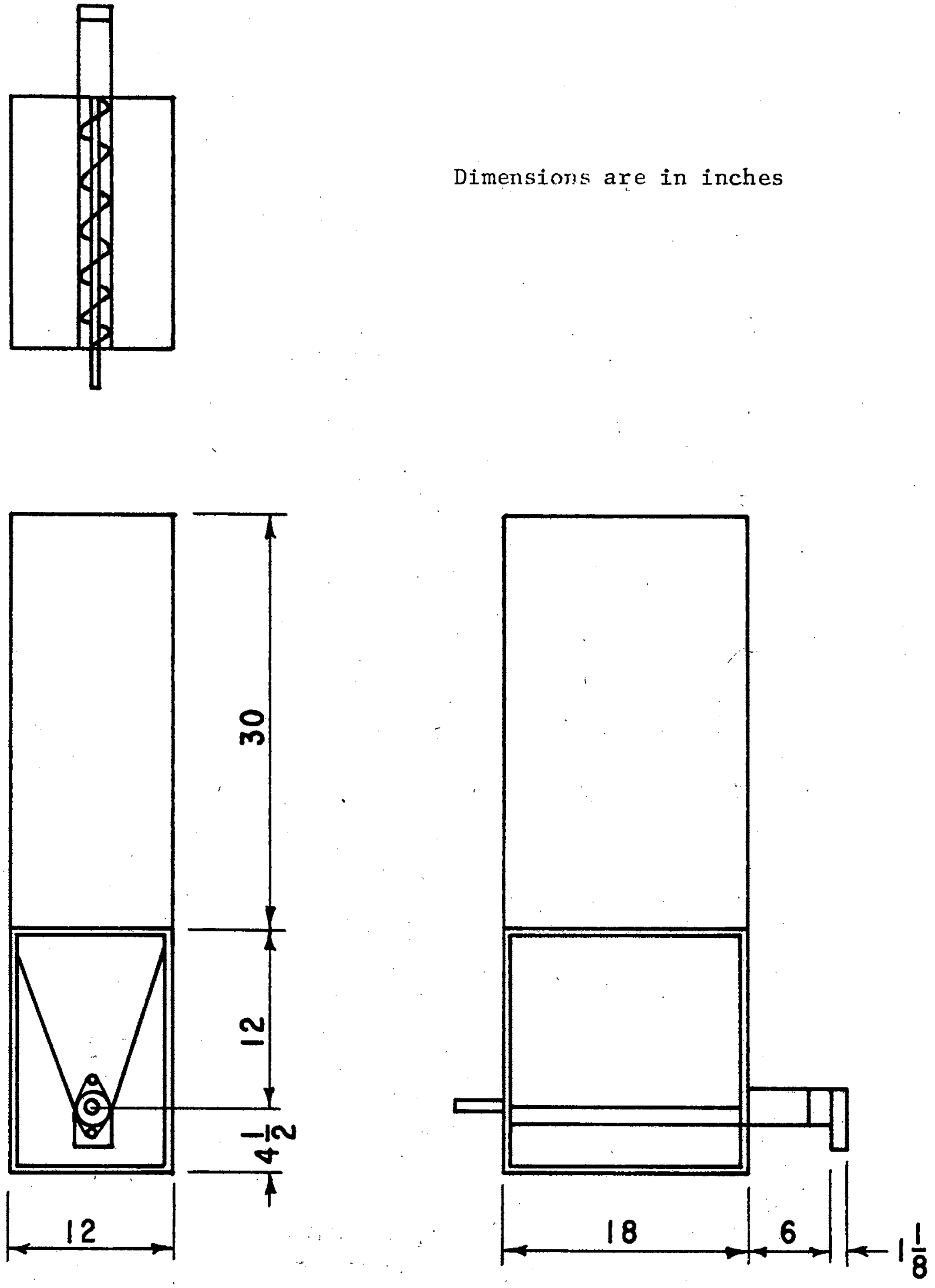
Note: Drill 17/64 dia, Tap 5/16-18NC, 6 Holes
Drill #7, Tap 1/4 - ZONC, 2 Holes
Material - 4" Dia x 3.50 Aluminum
Dimensions are in inches



Dimensions are
in inches

APPENDIX A-IV

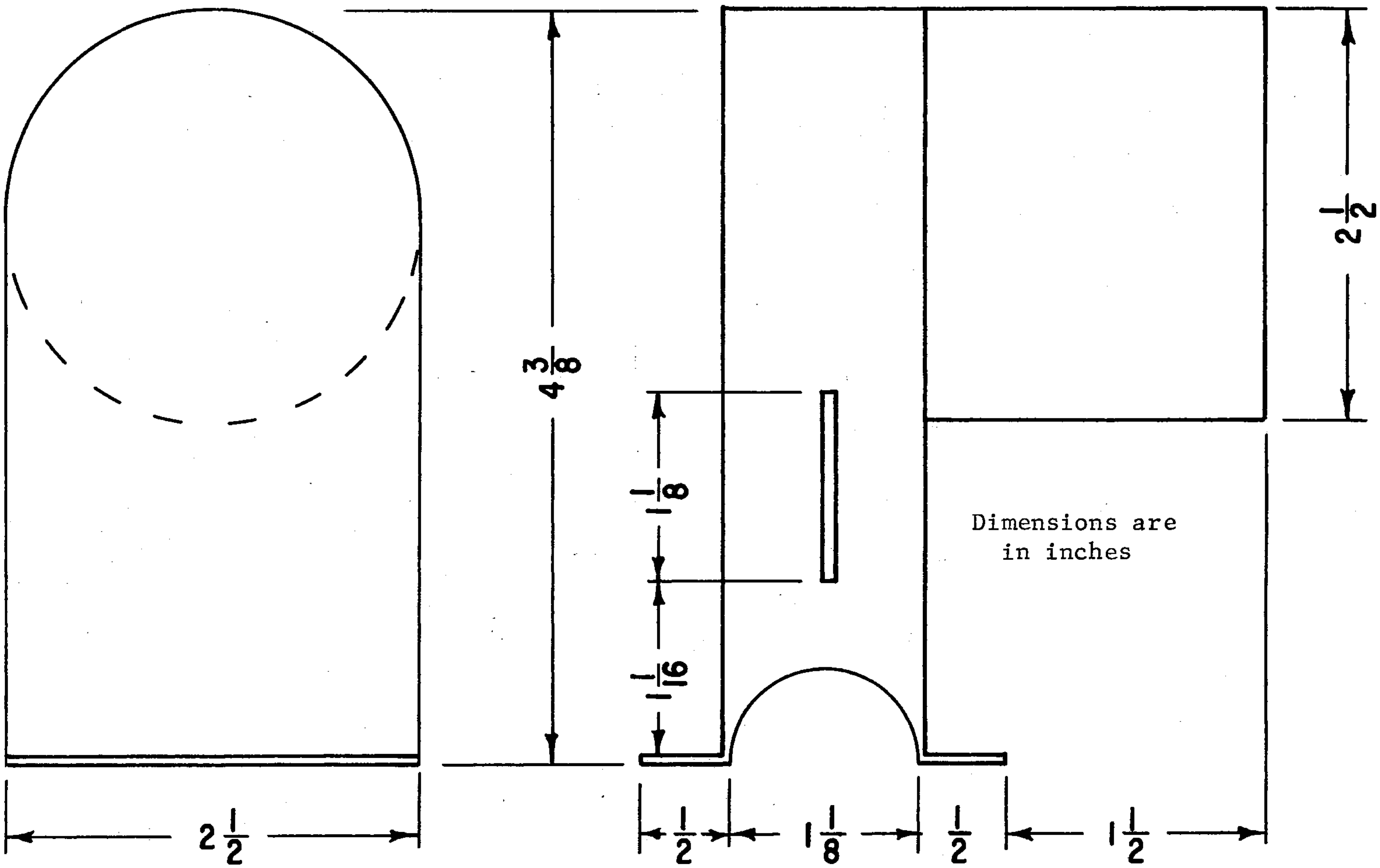
COANDA NOZZLE WALL DETAIL



Dimensions are in inches

APPENDIX A-V

MATERIAL FEEDING DEVICE



Dimensions are in inches

APPENDIX A-VI

FEEDER DOWNSPOUT

APPENDIX B

COMPUTER PROGRAMS FOR PRESSURE AND FLOW CALCULATIONS

APPENDIX B-I

FLOW CALCULATION FOR ROTAMETER CALIBRATION

```
1.    Get List (h, df, da)
2.    V = SQRT (2 * 32.2 * h * df/(12 *da))
2.5   V = V * 60
3.    Put List (V)
4.    Q = v * .0037
5.    Put List (Q)
```

APPENDIX B-II

VELOCITY CALCULATION FOR ONE INCH PIPE CALIBRATION

```
1.   Get List (h)
2.   V = SQRT (2 *32.2 * h * df/(12 * da))
3.   V = V * 60
4.   Put List (V)
```

APPENDIX B-III

FLOW CALCULATION FOR FREE AIR MEASUREMENT

```
1.     ST:    Get List (rno, d, vel, p1, p2)

2.            q1 = 200.913 - 478,856 * rno + 400.609 * rno ** 2
              -107,359 * rno ** 3

3.            q1 = q1 * SQRT (.074158/d)

4.            v2 = 319.578 + .509 * vel + .00015 * vel ** 2
              -.0000000166 * vel ** 3

5.            q2 = v2 * .849/144

5.5           qt = q1 + q2

6.            press = (p2 - p1) * .3939 * .3613

7.            Put List (q1, q2, qt, press)

8.            GO to ST
```

APPENDIX B-IV

FLOW AND PRESSURE CALCULATIONS FOR MATERIAL CONVEYING CAPACITY

```
ST:     Get List (rno, h, hm, hw, mwh)

        q1 = 200.913 - 478.856 * rno + 400.609 * rno ** 2
        -107.359 * rno ** 3
        q1 = q1 * SQRT (.074158/da)

        V = SQRT (2 * 32.2 * h * df/(12 *da))

        V = V * 60

        V2 = 319.5782432 + .5094530 * V + .0001505915
        * V ** 2 -.0000000166 * v ** 3

        q2 = V2 * .849/144

        qt = q1 + q2

        P32 - hm * .4912/.827

        P38 = hw * .03613

        PDC = mwh * .03907 * .03613

        Put List (q1, V2, q2, qt, p32, p38, PDC)

        Go to ST
```

APPENDIX B-V

AIR DENSITY CALCULATION FOR ALL FLOW CALCULATIONS

```
ST:     Get List (bp, vp, t)
        da = (bp -.38 * vp) /((t + 460) * .754)
        Put List (da)
        Go to ST
```

APPENDIX C

COANDA NOZZLE TEST DATA

APPENDIX C-I

COANDA NOZZLE FREE AIR TEST DATA AND CALCULATION

Slot Width	Air Density (lb/ft^3)	Rotameter Number	Nozzle Press. (PSI)	Primary Air Flow (CFM)	Secondary Vol. Head (in. Red Oil)	Secondary Velocity (FPM)	Total Air Flow (CFM)	Line Press. (PSI)
.006 in.	.0712	1.0	40	15.62	1.7	4874	41.905	.768
		1.1	49	16.34	2.0	5286	44.457	.896
	.0705	1.0	43	15.699	1.75	4969	42.42	.817
		1.05	49	15.90	1.85	5109	43.25	.896
	.0724	1.0	45	15.732	1.75	4980	40.092	.853
		1.05	49	15.935	1.85	5120	43.33	.903
.008 in.	.0724	1.0	18	15.49	1.0	3707	35.725	.469
		1.1	25	16.2067	1.35	4307	39.678	.661
		1.2	32	17.859	1.7	4833	43.95	.839
		1.3	38	19.797	1.9	5109	47.15	.981
	.0696	1.0	20	15.8	.95	3685	35.91	.512
		1.1	28	16.529	1.25	4227	39.58	.704
		1.2	34	18.215	1.45	4552	42.937	.889
		1.25	38	19.208	1.75	5001	46.078	.946
	.0702	1.0	23	15.73	1.09	3930	37.19	.569
		1.1	32	16.4587	1.45	4533	41.086	.775
		1.2	39	18.137	1.65	4835	44.237	.946

APPENDIX C-I (Continued)

Slot Width	Air Density (lb/ft^3)	Rotameter Number	Nozzle Press. (PSI)	Primary Air Flow (CFM)	Secondary Vol. Head (in. Red Oil)	Secondary Velocity (FPM)	Total Air Flow (CFM)	Line Press. (PSI)
.010	.0724	1.0	12.5	15.49	.675	3045	31.991	.369
		1.1	16	16.2067	.85	3417	34.8162	.498
		1.2	21	17.859	1.25	4144	40.47	.654
		1.275	24	19.322	1.4	4386	43.20	.739
		1.3	26	19.797	1.5	4540	44.46	.804
		1.4	32	21.369	1.7	4833	47.46	.946
	.0696	1.0	13	15.8	.65	3048	32.31	.377
		1.1	18	16.529	.9	3586	36.08	.547
		1.2	23	18.215	1.15	4054	40.347	.704
		1.3	29	20.19	1.35	4393	44.108	.88
		1.35	33	21.82	1.5	4630	46.19	.946
	.0702	1.0	13	15.73	.65	3035	32.17	.384
		1.1	18	16.458	1.02	3802	37.218	.533
		1.2	23	18.137	1.29	4275	41.44	.704
		1.3	29	20.1	1.42	4486	44.49	.874
		1.35	32	20.99	1.53	4656	46.22	.953
.012	.0712	1.0	11	15.62	.35	2211	27.43	.2759
		1.1	15	16.34	.65	3013	32.66	.4196
		1.2	19	18.009	.8	3343	36.203	.547

APPENDIX C-I (Continued)

Slot Width	Air Density (lb/ft^3)	Rotameter Number	Nozzle Press. (PSI)	Primary Air Flow (CFM)	Secondary Vol. Head (in. Red Oil)	Secondary Velocity (FPM)	Total Air Flow (CFM)	Line Press. (PSI)
.012	.0712	1.3	23	19.96	.95	3643	39.8449	.6614
	.0696	1.0	9	15.8	.45	2536	29.41	.298
		1.1	12	16.529	.65	3048	33.045	.384
		1.2	14	18.215	.79	3360	36.50	.512
		1.3	18	20.19	.95	3685	40.30	.63
		1.4	22	21.79	1.1	3965	43.446	.782
		1.45	23.5	22.249	1.15	4054	44.38	.839
	.0704	1.0	9	15.71	.45	2521	29.24	.313
		1.1	12	16.43	.59	2887	32.036	.398
		1.2	14	18.11	.85	3466	36.997	.51
		1.3	18	20.07	.95	3664	40.07	.647
		1.4	22	21.67	1.25	4203	44.597	.789
		1.45	24	22.12	1.35	4368	45.91	.867
.014	.0726	1.0	7	15.47	.2	1655	24.31	.200
		1.1	8	16.18	.3	2027	26.99	.270
		1.2	9	17.83	.4	2341	30.36	.348
		1.3	12	19.77	.6	2867	35.26	.44
		1.35	13	20.64	.7	3097	37.43	.476
		1.4	13.5	21.34	.75	3206	38.75	.536

APPENDIX C-I (Continued)

Slot Width	Air Density (lb/ft^3)	Rotameter Number	Nozzle Press. (PSI)	Primary Air Flow (CFM)	Secondary Vol. Head (in. Red Oil)	Secondary Velocity (FPM)	Total Air Flow (CFM)	Line Press (PSI)
.014	.0726	1.45	14.5	21.78	.8	3311	39.79	.593
	.0696	1.0	7	15.80	.25	1890	25.87	.263
		1.1	8	16.529	.37	2299	28.82	.327
		1.2	9.5	18.215	.47	2592	32.14	.3769
		1.3	12	20.19	.57	2854	35.60	.476
		1.4	14	21.795	.75	3274	39.59	.576
		1.45	15	22.249	.75	3274	40.049	.632
	.0704	1.0	7	15.71	.25	1879	25.72	.227
		1.1	8.5	16.435	.35	2224	28.31	.298
		1.2	10	18.11	.49	2631	32.2	.391
		1.3	12	20.07	.57	2838	35.39	.476
		1.4	14	21.67	.69	3122	38.608	.576
		1.45	15.5	22.12	.82	3404	40.658	.647
.016	.0726	1.0	3	15.47	.2	1655	24.3138	.170
		1.1	6	16.18	.22	1736	25.446	.232
		1.2	7	17.8347	.3	2027	28.64	.277
		1.3	8.5	19.77	.35	2190	31.46	.348
		1.4	9.5	21.34	.45	2483	34.658	.418
		1.45	10	21.78	.5	2617	35.85	.448

APPENDIX C-I (Continued)

Slot Width	Air Density (lb/ft^3)	Rotameter Number	Nozzle Press (PSI)	Primary Air Flow (CFM)	Secondary Vol. Head (in. Red Oil)	Secondary Velocity (FPM)	Total Air Flow (CFM)	Line Press. (PSI)
.016	.0696	1.0	5	15.8	.18	1604	24.38	.170
		1.1	6	16.529	.21	1732	25.77	.242
		1.2	7.5	18.215	.29	2036	29.069	.036
		1.3	9	20.19	.35	2236	32.137	.369
		1.4	10	21.79	.41	2420	34.76	.448
		1.45	10.5	22.249	.45	2536	35.864	.476
	.0704	1.0	5	15.71	.15	1456	23.547	.199
		1.1	6.5	16.435	.25	1879	26.42	.2418
		1.2	7.5	18.11	.3	2059	29.089	.284
		1.3	8.5	20.077	.39	2347	32.636	.369
		1.4	10	21.67	.45	2521	35.2	.448
		1.45	10.5	22.12	.49	2631	36.27	.476
.018	.0726	1.0	3	15.47	.1	1170	21.927	.184
		1.1	5	16.18	.2	1655	25.02	.21
		1.2	6.5	17.83	.25	1851	27.699	.256
		1.3	7.5	19.77	.3	2027	30.57	.298
		1.4	8.5	21.34	.34	2158	32.8577	.3627
		1.45	9	21.78	.4	2341	34.31	.398
	.0696	1.0	4	15.8	.13	1363	23.18	.156

APPENDIX C-I (Continued)

Slot Width	Air Density (lb/ft^3)	Rotameter Number	Nozzle Press (PSI)	Primary Air Flow (CFM)	Secondary Vol. Head (in. Red Oil)	Secondary Velocity (FPM)	Total Air Flow (CFM)	Line Press. (PSI)
.018	.0696	1.1	5	16.529	.15	1464	24.4068	.199
		1.2	6	18.21	.2	1690	27.2388	.25
		1.3	7.5	20.19	.25	1890	30.26	.32
		1.4	8	21.79	.3	2070	32.8336	.376
		1.45	8.5	22.249	.33	2171	33.837	.398
	.0705	1.0	5	15.699	.13	1354	23.035	.149
		1.1	6	16.42	.15	1454	24.25	.199
		1.2	7	18.098	.18	1593	26.62	.241
		1.3	8	20.062	.21	1721	29.247	.327
		1.4	8.5	21.656	.34	2190	33.348	.384
		1.45	9	22.107	.4	2375	34.82	.419
.020	.0726	1.0	3	15.47	.1	1170	21.927	.128
		1.1	5	16.18	.12	1282	23.172	.184
		1.2	5.5	17.8347	.15	1433	25.558	.213
		1.3	6	19.77	.175	1548	28.0688	.256
		1.4	7	21.34	.2	1655	30.18	.312
		1.45	7.5	21.78	.22	1736	31.047	.341
	.0696	1.0	3	15.8	.05	845	20.797	.145
		1.1	5	16.529	.08	1069	22.519	.194

APPENDIX C-I (Continued)

Slot Width	Air Density (lb/ft^3)	Rotameter Number	Nozzle Press (PSI)	Primary Air Flow (CFM)	Secondary Vol. Head (in. Red Oil)	Secondary Velocity (FPM)	Total Air Flow (CFM)	Line Press. (PSI)
.020	.0696	1.2	6	18.21	.11	1254	25.069	.227
		1.3	6	20.19	.15	1464	28.069	.256
		1.4	7	21.79	.2	1690	30.819	.308
		1.45	8	22.249	.24	1852	32.12	.352
		1.0	3	15.699	.07	993	21.345	.170
		1.1	4	16.42	.1	1187	22.96	.199
		1.2	5	18.098	.13	1354	25.43	.242
		1.3	6	20.62	.14	1405	26.64	.256
		1.4	7	21.656	.18	1593	30.177	.298
		1.45	7	22.107	.23	1801	31.7	.341

APPENDIX C-II

FREE AIR TEST OF THE COANDA NOZZLE WITH GRAIN BIN ATTACHED

Slot Width	Air Density (lb/ft^3)	Rotameter Number	Nozzle Press (PSI)	Primary Air Flow (CFM)	Secondary Vel. Head (in. Red Oil)	Secondary Velocity (FPM)	Total Air Flow (CFM)	Line Press. (PSI)
.012	.072	1.0	9	15.53	.4	2134	28.116	.273
		1.1	11	16.25	.55	2520	31.11	.356
		1.2	14	17.90	.75	2966	35.40	.475
		1.3	18	19.85	.97	3388	39.83	.617
		1.4	22	21.43	1.21	3785	43.75	.772
		1.45	24	21.87	1.28	3891	44.81	.831
.010	.072	1.0	13	15.53	.65	2752	31.76	.344
		1.1	18	16.25	.95	3352	36.02	.564
		1.2	24	17.91	1.15	3692	39.67	.683
		1.3	28	19.85	1.40	4061	43.80	.843
		1.35	33	20.72	1.5	4193	45.45	.950

APPENDIX C-III

TOTAL SYSTEM FREE AIR TEST DATA AND CALCULATIONS

Slot Width	Air Density (lb/ft^3)	Rotameter Scale	Sec. Open. Inch	Prim. Flow CFM	Nozzle Press. psi	h_2 Inches Red Oil	V_2 ft/min	Q_t CFM	Press. 32" psi	Press. 38' psi	Press. 1' from D.C.psi	ΔP 38' psi
.012 Inch	.0708	1.0	1	15.66	9	.08	1000	21.61	.368	.142	.002	.226
		1.1	1	16.38	11	.10	1107	22.91	.498	.180	.005	.318
		1.2	1	18.06	14	.15	1325	25.87	.635	.243	.008	.392
		1.3	1	20.02	18	.19	1481	28.75	.831	.316	.001	.515
		1.4	1	21.61	22	.2	1518	30.56	1.063	.390	.001	.673
		1.45	1	22.06	24	.22	1590	31.43	1.187	.426	.001	.761
.010 Inch	.0714	1.0	1	15.66	13	.13	1242	22.99	.498	.185	.005	.313
		1.1	1	16.38	18	.17	1405	24.67	.712	.275	.008	.437
		1.2	1	18.06	23	.22	1590	27.43	.902	.352	.014	.550
		1.3	1	20.02	28	.25	1694	30.00	1.128	.433	.018	.695
		1.35	1	20.90	34	.25	1694	30.89	1.306	.483	.022	.823
.014 Inch	.0714	1.0	1	15.66	7	.03	709	19.84	.296	.117	.004	.179
		1.2	1	18.06	9	.06	901	23.37	.475	.185	.007	.290
		1.4	1	21.61	14	.08	1009	27.56	.742	.293	.012	.449
		1.45	1	22.06	15	.11	1153	28.86	.819	.311	.012	.508

APPENDIX C-IV

MATERIAL CONVEYING TEST DATA AND CALCULATIONS

Primary Flow	Air Density (lb/ft^3)	Grain Flow lb/min	Sec. Open. Inch	Rotameter Scale	Nozzle Press. psi	h_2 Inches Red Oil	V_2 ft/min	Q_t CFM	Press. 32" psi	Press. 38' psi	Press. 1' from D.C. psi	ΔP 38' psi
20.74 CFM	.0719	4.62	1	1.35	19	.01	529	23.86	.861	.334	.011	.537
		4.52	3/4	1.35	19	.01	529	23.86	.890	.338	.012	.552
		4.4	1/2	1.35	19	.01	529	23.86	.861	.329	.012	.537
		4.38	1/4	1.35	19	.01	529	23.86	.846	.320	.011	.520
20.77 CFM	.07169	4.06	1/4	1.35	19	.01	529	23.89	.890	.316	.011	.574
		3.84	1/2	1.35	19	.01	529	23.89	.861	.320	.012	.541
		3.46	3/4	1.35	19	.01	529	23.89	.890	.316	.012	.574
		3.56	1	1.35	19	.01	529	23.89	.861	.309	.012	.552
		3.56	1	1.35	19	.01	529	23.89	.831	.311	.012	.520
		3.56	3/4	1.35	19	.01	529	23.89	.831	.309	.011	.522
		3.64	1/2	1.35	19	.01	529	23.89	.831	.313	.011	.518
		3.18	1/4	1.3	19	.01	529	23.89	.772	.261	.011	.511
18.96 CFM	.0714	2.4	1	1.25	16	.02	628	22.66	.712	.261	.008	.451
		2.4	3/4	1.25	16	.02	628	22.66	.683	.250	.008	.433
		2.4	1/2	1.25	16	.02	628	22.66	.683	.241	.008	.442
		2.38	1/4	1.25	16	.02	628	22.66	.683	.250	.009	.433
		2.5	1/4	1.25	16	.02	628	22.66	.683	.257	.009	.426
		2.4	1/2	1.25	16	.02	628	22.66	.683	.250	.008	.433

APPENDIX C-IV (Continued)

Primary Flow	Air Density (lb/ft^3)	Grain Flow lb/min	Sec. Open. Inch	Rota-meter Scale	Nozzle Press. psi	h_2 Inches Red Oil	V_2 ft/min	Q_t CFM	Press. 32" psi	Press. 38' psi	Press. 1' from D.C. psi	ΔP 38' psi
18.96 CFM	.0714	2.4	3/4	1.25	15	.02	628	22.66	.653	.248	.008	.405
		2.36	1	1.25	15	.02	628	22.66	.641	.239	.008	.402
18.88 CFM	.0720	2.4	1.0	1.25	15.5	.02	626	22.58	.653	.252	.008	.401
		2.4	3/4	1.25	15.5	.02	626	22.58	.653	.243	.008	.410
		2.4	1/2	1.25	15.5	.02	626	22.58	.653	.234	.008	.419
		2.34	1/4	1.25	15.5	.02	626	22.58	.623	.246	.008	.377
		1.30	1/4	1.25	15.5	.05	837	23.82	.668	.241	.009	.427
		1.30	1/2	1.25	15.5	.05	837	23.82	.668	.246	.009	.422
		1.30	3/4	1.25	15.5	.05	837	23.82	.638	.237	.009	.401
		1.28	1	1.25	15.5	.05	837	23.82	.602	.232	.009	.370
		1.28	1	1.25	15.5	.05	837	23.82	.697	.250	.009	.447
		1.28	3/4	1.25	15.5	.05	837	23.82	.668	.243	.009	.425
		1.28	1/2	1.25	15.5	.05	837	23.82	.638	.237	.009	.401
		1.28	1/4	1.25	15.5	.05	837	23.82	.638	.237	.009	.401
		1.3	1/4	1.25	15.5	.05	837	23.82	.638	.237	.009	.401
		1.3	1/2	1.25	15.5	.05	837	23.82	.638	.237	.009	.399
		1.3	3/4	1.25	15.5	.05	837	23.82	.638	.239	.009	.404
		1.3	1	1.25	15.5	.05	837	23.82	.638	.234	.009	.404
		2.1	1	1.25	15.5	.03	705	23.04	.683	.255	.088	.428

APPENDIX C-IV (Continued)

Primary Flow	Air Density (lb/ft^3)	Grain Flow lb/min	Sec. Open. Inch	Rota-meter Scale	Nozzle Press. psi	h_2 Inches Red Oil	V_2 ft/min	Q_t CFM	Press. 32" psi	Press. 38' psi	Press. 1' from D.C. psi	ΔP 38' psi
18.88 CFM	.0720	2.1	3/4	1.25	15.5	.03	705	23.04	.653	.252	.009	.401
		2.1	1/2	1.25	15.5	.03	705	23.04	.668	.246	.009	.422
		2.0	1/4	1.25	15.5	.03	705	23.04	.668	.248	.008	.420
		2.0	1/4	1.25	15.5	.03	705	23.04	.668	.252	.009	.416
		2.0	1/2	1.25	15.5	.03	705	23.04	.668	.250	.009	.418
		2.0	3/4	1.25	15.5	.03	705	23.04	.668	.241	.009	.427
		2.0	1	1.25	15.5	.03	705	23.04	.659	.243	.009	.416
18.97 CFM	.0713	2.2	1	1.25	16	.03	707	23.15	.712	.261	.009	451
		2.16	3/4	1.25	16	.03	707	23.15	.712	.261	.009	451
		2.16	1/2	1.25	16	.03	707	23.15	.712	.252	.009	460
		2.1	1/4	1.25	16	.03	707	23.15	.697	.243	.009	454

VITA

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Candidate for the Degree of

Master of Science

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