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AN AUTOMATED SYSTEM FOR MEASURING THE MASS FLOWRATE OF POWDERS IN TRANSPORT LINES

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A new automated particle transport (APT) system has been developed for studying the dissemination of bulk powders into deagglomerated aerosols. It consists of a 1.12-inch ID transport line with a spout-fluidized bed feeder. The particles are transported from an aerated annulus into the transport line and collected in a closed can or bag filter. Two separate feed lines supply the air necessary to operate the transport line and aerate the particles in order that they flow smoothly into the transport line. An IBM PC AT computer clone equipped with a Data Translation DT 2806 multifunction input-output board and A to D and D to A modules (DTX 311 and 328) is used for both control and data acquisition. A fluid mechanical model of the flow has been developed and the APT system will be used to verify it. Experiments will be conducted to measure the choking velocity, drag coefficient, fluid and particle flowrates, and pressure distribution in the line. Finally, tests have shown the system meets the flow specification of transporting solid particles at the rate of 5 lb/min for 5 min set by CRDEC. This system is being incorporated into the Combat Vehicle Defensive Obscuration (CVDOS) development effort.

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PREFACE

The work described in this report was authorized under Contract No. DAAA15-86-K-0016. This work was started in September 1988 and completed in September 1989.

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This report has been approved for release to the public.

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AN AUTOMATED SYSTEM FOR MEASURING THE MASS FLOWRATE OF POWDERS IN TRANSPORT LINES

1. INTRODUCTION

Fluidization and pneumatic transport of fine particles are integral processes in the dissemination of bulk powders into deagglomerated particulate aerosols. There exists the need to optimize the design characteristics of the US Army powder disseminators to maximize the deagglomerated yield of solid infrared smokes. This paper describes work performed at Rensselaer Polytechnic Institute (RPI) and the Chemical Research Development and Engineering Center (CRDEC) to research a) the pneumatic transport of fine powders and coarse particles through pipes and nozzles and b) the fluidization of bulk powders, as pertains to the aerosolization of solid infrared smoke materials via present US Army solid particle dissemination systems.

A fluid mechanical model for the flow of solid particles in a vertical transport line with a spout-fluidized bed feeder has been developed at RPI. To verify this model, the APT system has been built and experiments will be conducted to measure the choking velocity, drag coefficient, fluid and particle flowrates and the pressure distribution in the line.

A general sampled data PID control system runs the transport line and feeder, periodically samples and records selected sensor and set point readings for off-line analysis. This system has been implemented on an IBM PC AT clone and customized to maintain constant gas and solid flowrates and relative humidity in the transport line.

2. THEORY OF VERTICAL PNEUMATIC TRANSPORT

2.1 *Basic equations*

A new theory is developed for predicting the particle transport rate as well as the axial gas and solid velocity profiles within a vertical transport tube. One of the unique aspects of this new theory is that it minimizes the experimental information required to predict the particle transport rate. Specifically only a knowledge of the inlet gas and particle flowrates and the axial pressure profile existing within the transport line are required for a first principles prediction of the basic transport parameters.

The starting point of our analysis are the one dimensional steady state mass and momentum equations. Assuming negligible shear force at the wall of the transport tube and radially averaged velocity, pressure and voidage, these equations take the following form:

$$\varepsilon_t u_t = c_1 \tag{1}$$

and

$$(1-\varepsilon_t)v_t = c_2 \tag{2}$$

Equation (1) and (2) above are the appropriate mass conservation expressions for the gas and solid phases. The momentum equation for each phase is

$$\rho_f \frac{d}{dz}(\varepsilon_t u_t^2) = -\varepsilon_t \frac{dP_t}{dz} - \beta_A(u_t - v_t)^2 \tag{3}$$

and

$$\rho_p \frac{d}{dz}((1-\varepsilon_t)v_t^2) = -(1-\varepsilon_t)\frac{dP_t}{dz} + \beta_A(u_t - v_t)^2 - (1-\varepsilon_t)(\rho_p - \rho_f)g \tag{4}$$

Combining equations (3) and (4) and substituting equations (1) and (2) into the resulting expressions yields the following general voidage equation in terms of the pressure gradient.

$$\gamma(\varepsilon_t)\frac{d\varepsilon_t}{dz} + (1-\varepsilon_t)(\rho_p - \rho_f)g = -\frac{dP_t}{dz} \tag{5}$$

where $\gamma(\varepsilon_t) = (\rho_f c_1^2/\varepsilon_t^2) - (\rho_p c_2^2/(1-\varepsilon_t)^2)$

From the above equation, the explicit dependency of the transport tube voidage on the axial pressure distribution is highlighted. Once this distribution along with appropriate inlet or outlet boundary conditions are known, a direct numerical solution of equation (5) is possible.

An alternative formulation in which the axial voidage profile is related to the drag is obtained if one multiplies equation (3) by $(1-\varepsilon_t)$, equation (4) by $-\varepsilon_t$ and combines the two resulting expressions. That equation is reproduced below.

$$\delta_1(\varepsilon_t)\,\frac{d\varepsilon_t}{dz} + \varepsilon_t(1-\varepsilon_t)\,(\rho_p - \rho_f)g = \beta_A\,\delta_2(\varepsilon_t) \qquad (6)$$

where $\delta_1(\varepsilon_t) = [\varepsilon_t\,\rho_p\,c_2{}^2/(1-\varepsilon_t)^2)] + [\rho_f(1-\varepsilon_t)\,c_1{}^2/\varepsilon_t{}^2]$

and $\delta_2(\varepsilon_t) = [(c_1(1-\varepsilon_t) - c_2\,\varepsilon_t)/\varepsilon_t(1-\varepsilon_t)]^2$

This equation links the voidage explicitly to the drag. Similarly, a direct solution of equation (6) follows if $\beta_A(\varepsilon_t)$ and appropriate boundary conditions are available. The usefulness of equtions (5) and (6) for determining the choking gas velocity and the steady state drag coefficient, β_A, is highlighted in the next section. The choking gas velocity is important practically as it determines the minimum volumetric gas flowrate to move the particles through the line at a particular solids flowrate. The steady state drag coefficient is necessary for predicting performance above choking.

2.2 *Boundary conditions at choking and the choking gas velocity*

Although the boundary conditions at choking are unknown, reasonable assumptions can be made. Let us consider first the conditions at the top of the transport line. Assume that

$$\frac{d\varepsilon_t}{dz} = 0 \qquad \text{at} \qquad z = H_t \qquad (7)$$

Since equation (5) shows that $dv_t/dz = 0$ when $d\varepsilon_t/dz=0$, we are assuming that the particles are not accelerating at the top of the transport line. In a long transport line, this is undoubtedly the case.

Substituting equation (7) in equation (5) yields the voidage condition at the top of the line.

$$\varepsilon_t = 1 - [(-dP_t/dz)/(\rho_p - \rho_f)g] \qquad \text{at} \quad z = H_t \qquad (8)$$

At the inlet, we assume under choking conditions that

$$\gamma(\varepsilon_t) = 0 \qquad \text{at} \quad z = 0 \qquad (9)$$

It follows from equation (5) that

$$\varepsilon_c = 1 - [(-dP_t/dz)/(\rho_p - \rho_f)g] \qquad \text{at} \quad z = 0 \qquad (10)$$

Equations (8) and (10) are the equations for calculating the voidage at the inlet and outlet to the line. What is needed experimentally is the axial pressure profile which can then be differentiated numerically to determine the gradient. The inlet gradient is obviously more inaccurate because of the curvature there.

From equation (5)

$$\frac{c_1}{c_2} = \left(\frac{\rho_p}{\rho_f}\right)^{1/2} \frac{\varepsilon_c}{1-\varepsilon_c} \qquad \text{at} \quad z = 0 \qquad (11)$$

If the particle mass flowrate at choking is measured then c_1 can be calculated from equation (11). The volumetric flowrate of gas at choking is

$$Q_c = \frac{\pi}{4}\, d_t^2 \;\; c_1/\varepsilon_c \qquad (12)$$

Q_c is the minimum gas needed to move the particles through the transport line and ε_c is the minimum voidage. It is apparent that if our criteria for calculating $\varepsilon_t(0)$ and $\varepsilon_t(H_t)$ (equations 7 and 12) are correct then an axial pressure profile in the line is all that is required to obtain the conditions at choking. Solution of equation (5) gives the axial voidage profile in the line. The average voidage there is

$$\varepsilon_t = \int_0^1 \varepsilon_t(\zeta)\, d\zeta \tag{13}$$

The gas and particle velocity and slip velocity profiles are calculated using equations (3) and (4).

2.3 *Steady state drag coefficient, $\beta_s(\varepsilon_t)$.*

An expression for the steady state drag coefficient, $\beta_s(\varepsilon_t)$ follows directly from an evaluation of equation (6) at the top of the line. In this section of the line particle acceleration has ceased, $d\varepsilon_t/dz=0$ and equation (6) reduces to

$$\beta_s(\varepsilon_t) = \frac{\varepsilon_t(1-\varepsilon_t)(\rho_p - \rho_f)g}{\left[\frac{c_1(1-\varepsilon_t) - c_2\varepsilon_t}{\varepsilon_t(1-\varepsilon_t)}\right]^2} \qquad \text{at} \quad z = H_t \tag{14}$$

Equation (14) as shown is valid at and above the choking condition and relates $\beta_s(\varepsilon_t)$ to ε_t, c_1 and c_2. Further examination of this equation also reveals that the experimental determination of $\beta_s(\varepsilon_t)$ is a quite straightforward matter. All that is required for determining $\beta_s(\varepsilon_t)$ are a series of experiments in which c_1 and c_2 are varied and ε_t determined for each case. The latter parameter follows directly from a measurement of the outlet pressure gradient and is calculated directly from equation (8).

As indicated in equation (15) below, at the choking condition one less piece of experimental information is required. In terms of the solid mass flux, c_2 our expression for $\beta_s(\varepsilon)$ under choking conditions becomes

$$\beta_s(\epsilon_t) = \frac{\epsilon_t(1-\epsilon_t)(\rho_p - \rho_f)g}{\left[\dfrac{c_2\left[\left(\dfrac{\rho_p}{\rho_f}\right)^{1/2}\dfrac{\epsilon_c}{1-\epsilon_c} - \epsilon_t\right]}{\epsilon_t(1-\epsilon_t)}\right]^2} \qquad \text{at } z = H_t \qquad (15a)$$

The accelerating β_A in such system is obtained from an evaluation of equation (6) at the inlet to the draft tube under non-choking conditions. Since the first term appearing in that equation is always positive for a transport system one can conclude that β_A will always be larger than its non-accelerating counterpart, β_s. The enhancement due to the large gas acceleration at the inlet is given by the following result:

$$\beta_A/\beta_s = 1 + \frac{\delta_1\, d\epsilon_t/dz}{\epsilon_t(1-\epsilon_t)(\rho_p-\rho_f)g} \qquad (15b)$$

Experiments in the ATP system will allow us to determine the steady state, $\beta_s(\epsilon_t)$ for a variety of materials of widely different particle sizes and size distributions.

2.4 *Theory for the axial pressure profile*

A variational formulation similar to that posed in Morgan(1) for the axial pressure profile in a spouted bed of coarse particles has been devised for our transport line. In our analysis, radial pressure gradients are neglected and it is assumed that $-d^2P^*/d\zeta^2$ must decrease monotonically with axial distance, ζ. The genesis of this approach arises from the fact that all the experimental pressure profiles observed to date exhibit this characteristic. Even in those cases where a maximum is observed in the pressure profile one finds that $-d^2P^*/d\zeta^2$ decreases monotonically with ζ. Hence the following isoperimetric variational problem was posed for the axial pressure profile in the line. In Morgan et al.(2 and 3), the general formulation of this particular problem is discussed in detail.

Consider the functional

$$J(P_t^*) = \int_0^1 \sqrt{1 + \left(-\frac{d^2P_t^*}{d\zeta^2}\right)^2}\, d\zeta \qquad (16)$$

in terms of the dimensionless second derivative of pressure and distance to have an extremum where the admissible curves satisfy the boundary conditions

$$-d^2P_t^*/d\zeta^2 = \infty \quad \text{at} \quad \zeta = 0 \qquad (17)$$

$$-d^2P_t^*/d\zeta^2 = 0 \quad \text{at} \quad \zeta = 1 \qquad (18)$$

and the integral constraint functional

$$\int_0^1 \left(-\frac{dP^*}{d\zeta}\right) d\zeta = \frac{\Delta P_t}{\Delta P_{mF}} \qquad (19)$$

Physical justification for the boundary and integral conditions are briefly discussed below. Firstly, equation (17) follows from the requirement that a precondition for particle transport into the draft tube is the existence of a large accelerating potential at the entrance to the draft tube. The magnitude of this potential is bounded by the specification given in equation (17). The second boundary condition (eqn 18) follows from experimental observation that the pressure at the outlet to the line varies linearly with distance and that fluid acceleration has ceased. Differentiation of such a profile leads directly to equation (18). Intuitively, one can surmise that these two boundary conditions are natural limits for such systems. The integral constraint given in Equation 19 is a pressure drop specification.

General methods of solution for equations (16) through (19) are outlined in Weinstock(4). The solution to this system of equations is

$$\frac{\frac{-dP_t^*}{d\zeta}(\zeta) - \left(\frac{-dP_t^*}{d\zeta}\right)_{\zeta=0}}{\left(\frac{-dP_t^*}{d\zeta}\right)_{\zeta=1} - \left(\frac{dP_t^*}{d\zeta}\right)_{\zeta=0}} = [1-(1-\zeta)^2]^{1/2} \qquad (20)$$

Integration of equation (20) gives an expression for the pressure profile in the line. That equation is

$$P_t^*(\zeta) - P_t^*(0) = G(\zeta)\left[\left(\frac{-dP_t}{d\zeta}\right)_{\zeta=1} - \left(\frac{-dP_t}{d\zeta}\right)_{\zeta=0}\right] + \left(\frac{-dP_t}{d\zeta}\right)_{\zeta=0} \qquad (21)$$

where $G(\zeta) = 0.785 - 1/2\,[(1-\zeta)\sqrt{1-(1-\zeta)^2} + \text{Arc sin}\,(1-\zeta)]$

Evaluating the above result at $\zeta=1$ leads to the following pressure identity.

$$\Delta P_t/\Delta P_{mF} = 0.215\left(\frac{-dP_t^*}{d\zeta}\right)_{\zeta=0} + 0.785\left(\frac{-dP_t^*}{d\zeta}\right)_{\zeta=1} \qquad (22)$$

Equation (22) implies that only a knowledge of two of the terms appearing in that equation are required for a complete specification of the pressure profile given in equation (21). Presently there are no correlations available for the quantities appearing in equation (21). A future paper will address this issue. The experiment validity of both equations (21) and (22) have been established in a recent paper by Morgan et al.(5)

In our ATP system only direct measurements of the total gas flowrate, the solid feedrate and the exit pressure gradient at the ends of both the draft tube and spout-fluid bed annulus are required for a determination of c_1, c_2, $\beta_A(\varepsilon_t)$ and $P_t(z)$. Under choking conditions measurements of the solid feedrate, c_2 is not necessary. A detailed description of this system and results from our initial set of runs are summarized in the following section. Further details can be found in the MS thesis of Morton (1989). It should be noted that without our theoretical framework to guide us the development of the ATP system and the resulting control logic would have been impossible.

3. INSTRUMENTATION[6,7,8]

3.1 Description of the system

The APT System is revolutionary in that it is under complete computer control. Particles of any size or size distribution that can be fluidized can be transported in the line. After passing through the line the particles are separated from the gas by either a bag filter and a cyclone and then returned to the hopper in Figure 1 via a standpipe. For safety reasons when transporting micron sized particles the system has been designed so that all particles recirculate within it. The output of the sensors listed in Figure 1 are datalogged by the computer. The system has met CRDEC's design specification by transporting 5 lb of sand per minute for 5 minutes in actual tests described later.

A schematic diagram of the APT system is shown in Figure 1. The vertically mounted stainless steel transport line is 18 feet and 8 inches long. It is 1 1/4 inches OD with a wall thickness of 0.065 inches. To maintain constant air and particle mass flowrates and control of the humidity in the transport line requires three control loops. Loop 1 maintains the air flowrate in the transport line constant during a run. The computer makes a mass balance using the inputs of the flowmeters, F1, F2 and F3 (F4=F1+F2-F3). Loop 2 provides a constant axial pressure drop across the annulus during a run by adjusting the air flowrate F2. This keeps the solids feed rate into the transport line constant as the level of the solids in the hopper drops and thereby maintains a fixed axial pressure profile in the transport line. DP3 is constant during a run. Loop 3 maintains constant relative humidity of the air leaving the transport line by controlling the flowrate

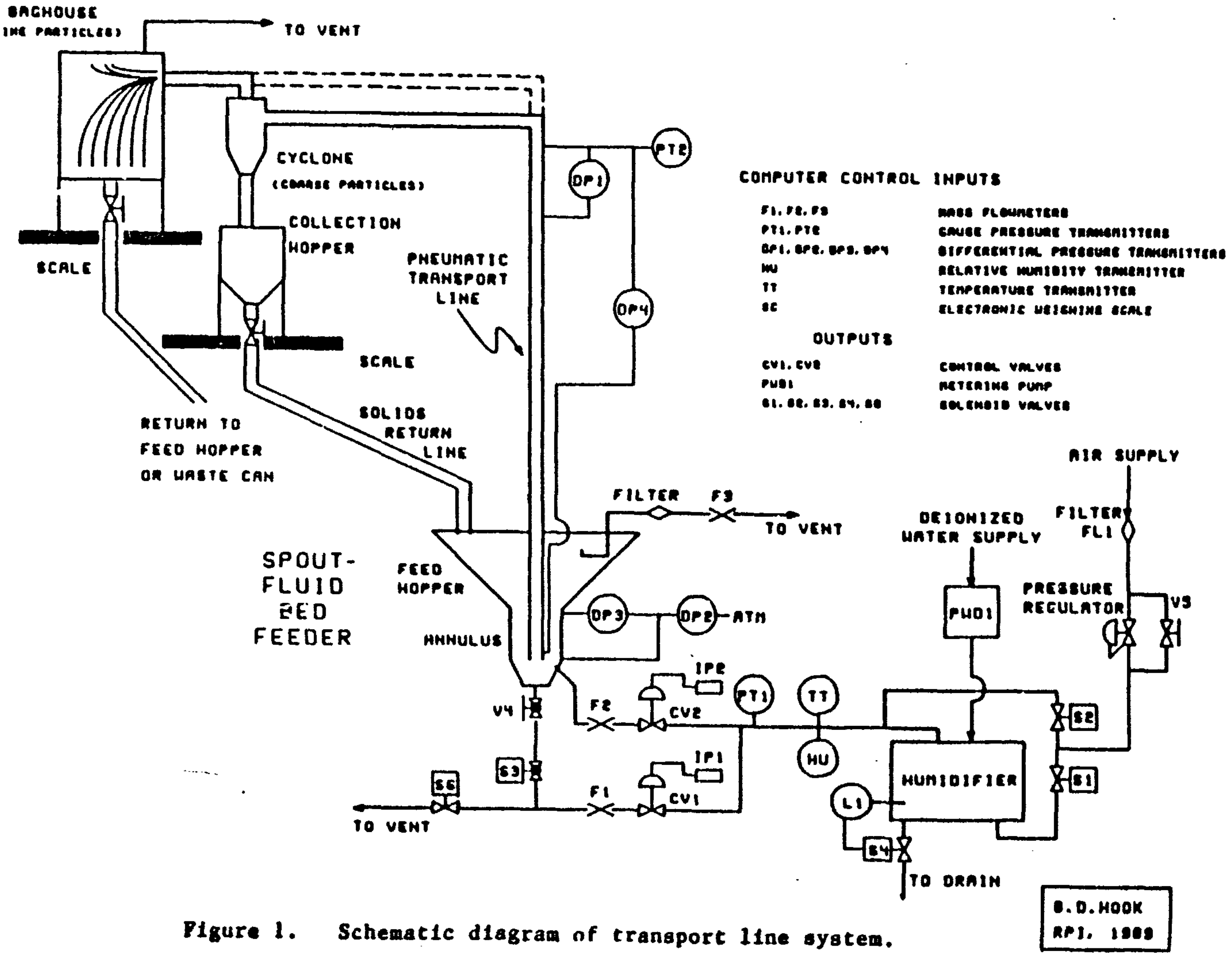

Figure 1. Schematic diagram of transport line system.

of water into the humidifier column with the peristaltic pump PWD1. The relative humidity of the humidifier is measured by the sensor, Hu.

There are 12 inputs and 4 outputs to the PC.

3.1.1 Inputs

Flowmeters: F1, F2 and F3
Humidity Sensor: Hu
Temperature Transmitter: TT
Pressure Transmitters: PT1 and PT2
Differential Pressure Transmitters: DP1, DP2, DP3, and DP4
Electronic Weighing Scale: SC

3.1.2 Outputs

Control Valves: CV1, CV2
Peristaltic Pump: PWD1

3.2 *Description of computer controlled transport line*

Computer Hardware

The RPI system consists of an IBM PC AT clone with 640 kilobytes of random access memory (RAM), a monochrome (Hercules compatible) graphics adapter, monochrome monitor, one high capacity 5 1/4 inch floppy disk drive, a 20 megabyte hard drive, and an Epson LQ 800 dot matrix printer.

3.3 Procedure for Startup

Mode	Action	Remarks
Startup	Set PR manually	Maintains constant air supply pressure downstream and limits system pressure.
	Open S1 and S6. Set control loop 1 to automatic and specify set point.	Air passing through humidifier at fixed flowrate.
	Set control loop 3 on automatic and specify set point.	Starts water flowing through the humidifier at a fixed flowrate. Relative humidity of air leaving transport line at PT2 is maintained constant by controlling water flowrate to humidifier.
	Datalog HU, TT, PT1 and F1 once steady state is reached.	Humidity, temperature, pressure and gas flowrate are recorded once steady state is reached.
	Set control loop 2 to automatic and specify set point. F2 is fixed by keeping DP3 constant.	Controls air flowrate through flowmeter F2 aerating solids in annulus. Limits flowrate in annulus below u_{mF} by fixing DP3 pressure drop maximum to $0.9\ \Delta P_{mF}$.
	Close S6. Open S3. Control loop 1 process variable switches from F1 to F4=F1+F2-F3.	Air passing through flowmeter F1 enters the spout-fluid bed feeder causing solids to flow in the transport line.
	Datalog F1, F2, F3, HU TT, PT1, PT2, DP1, DP2, DP3, DP4 and SC.	Experimental data for run.

3.4 Running, Shutdown and Emergencies.

Mode	Action	Remarks
Run	Run transport line for 5 minutes and shut down.	Datalog F1, F2, F3, HU, TT, PT1, PT2, DP1, DP2, DP3, DP4 and SC.
Shutdown	Close S3, open S6 and close S1 and S2.	Close air supply to system.
	Close CV1, CV2	Set loops 1 and 2 to manual with loop output equal to zero.
	Turn off PWD1	Shuts off water supply to humidifier. Sets loop 3 to manual with loop output equal to zero.
Power Failure	S1, S2, S3 and S6 close automatically.	
Computer Crash	Operator shuts down system.	Use irregularities in pressure profile as a guide.
Air supply too large	Close S3 and then S1 and S2 and shut down.	PT1 reads a pressure above that set on PR.
Air supply too small	Close S3 and shut down.	Flowrate not sufficient to maintain the particle terminal velocity at inlet to feeder in line containing F1.

3.4.1 Analog Sensor Inputs (12)

Analog inputs are used in two ways. First, they are needed to obtain the feedback signals necessary to run the control loops. Second, they are used to collect the data which will be analyzed after the experiment has been completed. The system has a maximum of 32 analog inputs. Only 12 are needed in an experiment.

3.4.2 Digital Outputs (4)

Digital outputs are used to activate on-off devices such as solenoid valves, warning lights and other on-off valves. The system has 8 general purpose user programmable digital outputs plus one dedicated output. Only three are needed to run an experiment. The user programmable outputs can be modified manually or automatically and sequenced at any time during an experimental run, or in addition, sequenced during startup. A dedicated digital output is used to indicate that one of the sensor alarms has been activated. This output can be used to activate any number of physical warnings devices such as buzzers, bells, or lights.

4. IN-HOUSE TESTING

On 15-16 Aug. 88, RPI and CRDEC successfully conducted an in-house testing at RPI facilities to evaluate the APT. A total of five trials conducted utilizing the APT with sand. A uniform flow was kept during the duration of each test. The tested material was collected in the collector can which was weighed prior to and after each trial. The results listed in the table below showed the APT is a highly data reliable system and capable of fluidizing and transporting particles without any malfunction.

Table: Summary of APT Experimental Data Using Sand
Tare Weight: 5 lb

Trial No.	Duration of Trial (min)	Total Weight of Material Transported (lbs)	Average Rate of Material Transport (lbs/min)
1	5	19.0	3.8
2	5	21.5	4.3
3	5	23.5	4.7
4	5	24.0	4.8
5	5	27.5	5.5

5. FUTURE WORK

The APT system could be modified to adapt to CRDEC - AAI - MRC Chamberlain Vehicle Enhanced Smoke System (VESS) prototypes and to produce a particulate stream whose flow properties can be measured. The measurements might include flow rate, and ratio of gas to solid in the stream at various time intervals and pressure drop. Several runs should be made to find the optimum output gas pressure of the VESS system when a mass flow rate of particulate of 5 lbs/min is obtained.

CRDEC has indicated interest in spraying 5 to 14 microns carbon fibers and brass particles. Both carbon fibers and brass particles stick together. Since the transport characteristics of fine particles is an area in need of research, the APT is the ideal model apparatus to study this problem.

6. CONCLUSIONS

The APT system was inspected by Mr. Prapas, CRDEC, APG and found the system to be reliable and in excellent working condition. The whole operation of the system is done by a computer program developed by RPI. The system is capable of fluidizing and transporting aeratable fine powders or coarse materials in the size range of 0.5 - 5 mm at a rate of 5 lbs/min for 5 minutes.

The APT is compatible with the CRDEC-AAI-MRC Chamberlain VESS prototypes. This makes APT the "number one" fluidizing system in the Army community.

NOMENCLATURE

c_1, c_2 = parameters defined in equations (1) and (2), m/s.
d_t = transport tube diameter, m.
g = gravitational acceleration, m/s^2.
G = function defined in equation (21).
H_t = transport tube length, m.
ΔP_{mF} = minimum fluidization pressure, Pa.
ΔP_t = pressure drop across transport tube, Pa.
P_t = pressure in transport tube, Pa.
P_t^* = dimensionless pressure in transport tube, $P_t/\Delta P_{mF}$.
Q_c = gas volumetric flowrate at choking, m^3/s.
u_t = interstitial gas velocity in transport tube, m/s.
v_t = particle velocity in transport tube, m/s.
z = dimensional axial distance, m.

<u>Greek Symbols</u>

β_A = accelerating drag coefficient defined in equation (15b), kg/m^4
β_s = steady state drag coefficient defined in equation (14), kg/m
δ_1, δ_2 = parameters defined in equations (6), kg/ms^2.
ε_c = voidage at choking condition.
ε_t = voidage in the transport tube.
γ = defined in equation (5), kg/ms^2.
ρ_f = fluid density, kg/m^3.
ρ_p = solid density, kg/m^3.
ζ = dimensionless distance, z/H_t.

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