MEASUREMENT OF THE CRITICAL DEPOSITION VELOCITY IN SLURRY TRANSPORT THROUGH A HORIZONTAL PIPE

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ABSTRACT

Critical Deposition Velocity (CDV) is an important design and operational parameter in slurry transport. Almost all existing correlations that are used to predict this parameter have been obtained experimentally from slurry transport tests featuring single solid species in the slurry mixture. No correlations have been obtained to describe this parameter when the slurry mixture contains more than one solid species having a wide range of specific gravities, particle size distributions and volume concentrations within the overall slurry mixture. There are no physical or empirical bases that can justify the extrapolation or modification of the existing single species correlations to include all these effects. New experiments must be carried out to obtain new correlations that would be suited for these types of slurries, and that would clarify the mechanics of solids deposition as a function of the properties of the various solid species.

Our goal in this paper is to describe a robust experimental technique for the accurate determination of the critical deposition velocity associated with the transport of slurries in horizontal or slightly inclined pipes. Because of the relative difficulty encountered during the precise determination of this useful operational parameter, it has been the practice to connect it with some transitional behavior of more easily measurable flow parameters such as the pressure drop along the slurry pipeline. In doing so the critical deposition velocity loses its unique and precise definition due to the multitude of factors that influence such transitional behaviors. Here, data has been obtained for single species slurries made up of washed garnet and water and flowing through a 1- inch clear pipe. The selected garnet had a narrow particle size distribution with a mean diameter of 100 μm, approximately. The critical deposition velocity was measured for garnet/water slurries of 10, 20, and 30 percent solids concentration by volume.

1. INTRODUCTION

Millions of gallons of toxic and radioactive waste are stored in large underground tanks at various DOE sites. In some situations, the waste is made up of a layer of settled solids, in sludge form, at the bottom of the tank with another layer of supernatant liquid on top of it. These underground storage tanks have a finite life and many have reached the point when it is prudent to remove the waste that is stored in them for safety reasons. The radioactive waste must eventually be retrieved and transported via slurry transfer lines to other storage facilities, or, to pretreatment plants for conditioning and preparation for permanent and safe long-term storage.

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In the past, several of these transfer lines (usually buried, 3 to 6 feet below ground) have been plugged by the flowing slurries. Due to the difficulty in locating, reaching and clearing these plugs, a new transfer line is usually built to replace the plugged line. Improved understanding of the mechanical and chemical properties of the waste slurries being transported, and the impact of the operating flow conditions on these properties, is needed to reduce the chances of plug formation in planned transfer lines. This work addresses one such need that is the determination of the onset of bed formation. Stationary beds begin to form when settled particles that have been dragging along the bottom of the transfer line, stop moving altogether due to insufficient flow velocity necessary to keep them in forward motion.

2. BACKGROUND

The physical properties of the radioactive wastes that are considered for retrieval and transport at the various DOE nuclear sites while not completely characterized at present, are expected to have severe chemical, physical and mechanical properties. The solid particles may agglomerate, attrite, stick to a pipe wall, or absorb some of the carrier liquid due to their morphology. The carrier liquids, in the presence of solid particulate, may have their specific gravities and viscosities increase, the slurry mixture may become non-Newtonian and even visco-elastic due to gelling. There are numerous operational situations that can cause a transfer line to be plugged suddenly (gelling due to temperature drop), or, gradually over a period of time (due to bed formation and adhesion to the pipe wall), or due to a combination of these and other unanticipated reasons. We are only concerned here with the precise determination of the "Critical Deposition Velocity", without consideration of any other chemical, physical or mechanical behavior.

The critical deposition velocity for slurry transport has been defined here as that average mixture velocity at which those solid particles that are being transported or dragged along the bottom of the pipe while in physical contact with it, stop moving all together. Further reduction of that average mixture velocity initiates the process of forming a settled bed. Such velocity is dependent on many slurry flow parameters and physical properties including the solids specific gravity, size distribution, volume concentration and settling velocity, and, the carrier liquid viscosity and specific gravity among others. This definition meets strict but practical operational engineering requirements for safe, stable and reliable slurry transport in pipelines.

The critical deposition velocity as a significant design and operation parameter for reliable slurry transport has not been theoretically modeled because of inadequate understanding of all the relevant physical phenomena involved. However, a variety of empirical critical velocity correlations exist in the open literature. In principle, these correlations can be tested against new slurry transport situations that are similar in nature to those from which a particular empirical correlation has been obtained. One of the earliest correlations is that of Durand and Condolios, [1], which is basically a representation of the transition velocity between laminar and turbulent flows for non-Newtonian slurries that follow a Bingham Plastic model. Initial thinking suggested that solids would settle fast when the flow became laminar and turbulent lateral diffusion disappeared. Wasp, et al, [2], modified Durand's relation, [1], to adequately represent the effect of the solids volume concentration and the mean particle size. Recently, a correlation

by Oroskar and Turian, [3], combined the work of several authors, and, in addition, accounted for the effect of dissipation of turbulent energy.

Unfortunately, most if not all the existing correlations were based on data featuring slurries with a single solid species; coal, sand, sulfur, etc. No correlations have been obtained from tests on slurries that simulate waste at the various DOE nuclear sites. In these slurries 5 or 6 different solid species are used to simulate the radioactive waste. Additional complications result from solid species with widely varying specific gravities and particle size distributions. In addition, each solid species will have a different concentration by volume within the overall slurry mixture. None of the existing critical velocity correlations can be extrapolated or modified with confidence to include all these effects. New experiments must be carried out to obtain correlations suited for these types of slurries and to help understand the mechanics of deposition as a function of the various slurry flow parameters.

3. THE EXPERIMENT

Critical deposition velocity of a particular slurry mixture flowing through a horizontal pipe can be determined by direct visual, or other indirect but non-intrusive observation methods, of the solid particles that are in contact with the bottom of the flow pipe. This requires that a section of the flow pipe must be clear (to the sensing device) and a suitable particle observation method must be available. In the present case, visual observations were made of pink garnet particles as they moved and eventually dragged along the bottom of a clear polycarbonate test section of the slurry pipe loop. The test is usually carried out by initially allowing the slurry mixture to flow at high speed such that homogeneous flow occurs. This condition that allows the solid particles to be uniformly distributed over the cross-section of the pipe, is maintained until stable, steady state flow is achieved. Photographing the slurry stream through the pipe bottom is then started. Shortly after the homogeneous flow is photographed, the mixture velocity is reduced in a gradual and controlled manner. As the mixture velocity is steadily reduced, the solids begin to drop out of suspension and form a thin moving bed of particles at the pipe's bottom. The critical deposition velocity corresponds to the instant when these solid particles that have been forming the moving bed along the bottom of the pipe stop moving, and begin to form a stationary bed.

Consider the simple situation when the solid particles have a narrow particle size distribution (nearly uniform size), slurry with a small overall volume concentration, but with several solids species having different specific gravities. Settling solids will start reaching the bottom of the pipe at different mixture velocities, the heavy ones will start dragging along the bottom of the pipe at a relatively higher mixture velocity followed by the lighter particles at correspondingly lower mixture velocities. Additional complexities will occur when a wide particle size distribution exists and the overall volume concentration of the solids is relatively high, thus allowing for particle – particle interaction, crowding and hindered settling to interfere with the logical process associated with the simpler situation. One should anticipate that all these factors influence the actual measured values of the critical deposition velocities.

Normally the critical velocity occurs near but slightly higher than that velocity at which the pressure drop is a minimum. The point of minimum pressure drop is sometimes associated,

on a physical flow map, as the beginning of the unstable/unsteady flow regime. Transport should never take place under such conditions. Engineering practice suggests that the minimum operating velocity for a slurry pipeline should be 2 to 3 ft/sec above the measured or estimated critical deposition velocity. This will ensure stable, safe and reliable slurry transport.

A. The Pipe Loop

The pipe loop is shown schematically (not to scale) in Figure 1. At the inlet end, labeled 'A' is a sturdy table that carried the pump - motor assembly. The pump was a stainless steel 8-stage centrifugal pump capable of delivering a large flow rate at high pressure even at the increased fluid density and viscosity when the slurry concentration was high. The pump was powered by a 7.5 H.P. motor with a 3500 rpm nominal speed. It was connected to a programmable variable frequency drive that was capable of starting the motor at any rpm below 3500, ramp it down linearly at any desired rate (by specifying the deceleration time), to any desired lower rpm, and, then repeat the process in the reverse direction.

At the discharge end (not shown here) the slurry flowing through the pipe loop was discharged into a mixing tank that maintained the high specific gravity solids in a nearly perfect homogeneous suspension. A suction pipe was immersed in the same tank to bring the slurry to the pump intake. The pipe loop was equipped with a TOSHIBA Electromagnetic Flow meter that was placed at the end of a long straight section of pipe, see Figure 1, to ensure its accuracy, a 6 ft length of 1-inch clear polycarbonate pipe, labeled 'B' in the Figure, and a sliding coupling, labeled 'C', specially designed to facilitate the replacement of the clear section of pipe.

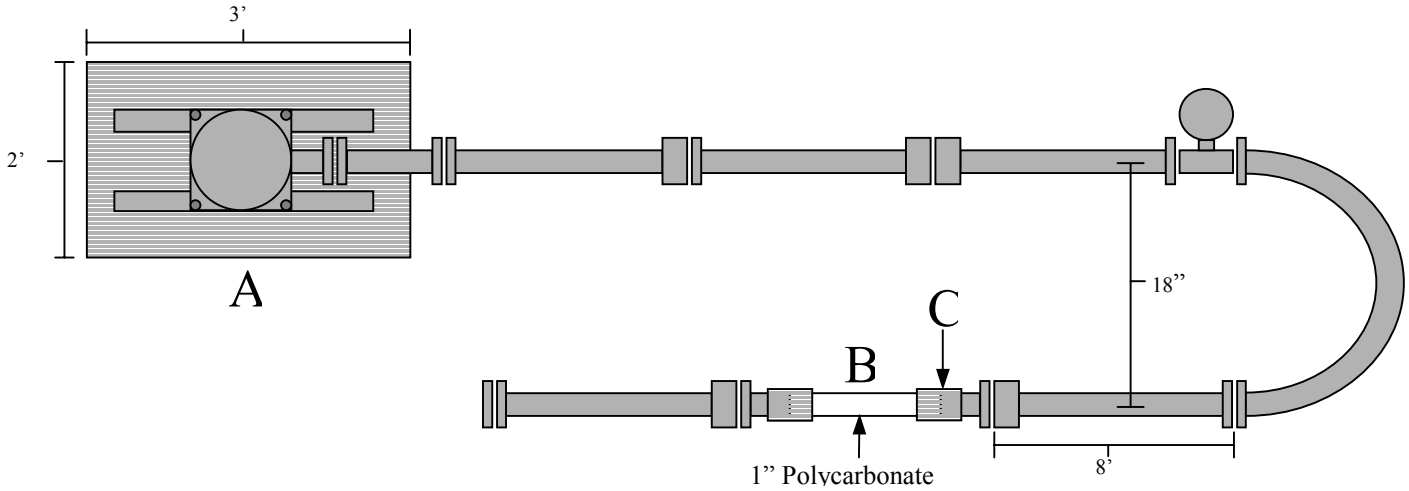

Figure 1. The Pipe Loop Test Facility

The pipe loop was aligned to maintain the straightness of the three connected 8 feet sections on the upstream and downstream sides of the loop. This required that the welding of the connecting flanges to the pipe sections be done with extreme care. Accurate horizontal leveling of the pipe loop, about 3 feet above ground, was maintained by providing support at eight points

using heavy duty adjustable tripod supports. The pipe loop was restrained at both ends to prevent any undesirable axial movement.

B. Instrumentation and Data Acquisition System

Data was gathered by placing a digital camera beneath the clear pipe section and aiming the lens upward towards the bottom of the clear pipe. It was possible to bring the camera relatively close to the pipe bottom and focus on the image of the flowing stream. The instrumentation and the data acquisition system are shown schematically in Figure 2 below.

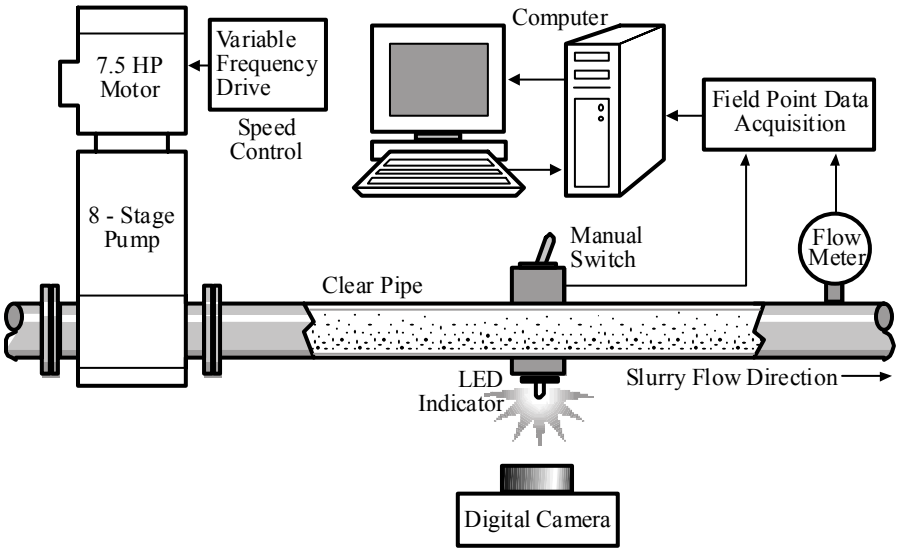

Figure 2. Schematic Diagram of the Instrumentation and the Data Acquisition Systems

Flow Meter

A TOSHIBA model LF410 Electromagnetic Flow meter along with a model LF400 converter was directly mounted on the pipe loop as shown in Figure 1. This non - intrusive device is particularly suited for slurry flow measurements. The flow meter displays the volume flow rate as well as the accumulated volume that passed through it starting from a given time, in any desired units. This information is also transmitted electronically to the data acquisition system. Before each test, the flow meter was calibrated at the operating solids concentration to verify the accuracy of its measurements. The absolute error in the flow meter readings never exceeded 5%, and was mostly in the 2% to 3% range.

Variable Speed Drive

The pump motor was connected to a variable frequency drive to control its operation. The drive can run the pump at any speed, and it can be programmed to decrease the pump speed at a prescribed linear rate. For this experiment, the maximum and minimum speeds were

specified based on calculation estimates. The maximum rpm produced homogeneous slurry flow and the minimum rpm produced a significant settled bed. The motor deceleration was selected to be sufficiently small as to not influence the fully developed nature of the flow. The variable frequency drive started the pump at the high speed, and decreased the rpm at the specified deceleration until the minimum rpm is reached. This provided an efficient, accurate and repeatable way of steadily decreasing the flow velocity. The variable frequency drive was connected to a toggle switch with ON/OFF settings. At the ON setting, the pump steadily ran at the high rpm. When the toggle switch was moved to the OFF setting, the ramping sequence began. At the end of the test run, the toggle switch was moved back to ON and the motor rpm was gradually accelerated back to the maximum rpm, thus resuspending the settled solids.

The variable speed drive was also connected to an LED indicator, which was mounted near the clear polycarbonate pipe. During the testing, when the pump was running at its maximum rpm, the LED indicator was illuminated. After the deceleration sequence was started, the LED indicator stayed lit until a specified RPM, slightly lower than the maximum rpm, was reached when it was dimmed. The data acquisition system registered the voltage pulse that resulted from the dimming of the LED indicator. This provided a correlation between the data recorded by the data acquisition system and the images photographed by the digital camera.

Digital Camera

A digital camera was used to photographically record the movement of the solid particles near the bottom of the clear section of the pipe loop. The camera was placed below and near the center of the clear polycarbonate pipe on a tripod, facing upward, such that both the pipe and the LED indicator described previously were in view, see Figure 2. The camera recorded the slurry images, the LED indicator as well as the time (internal to the camera) for each run. Since the time and the state of the LED indicator were recorded both by the camera and by the data acquisition system, the data on the two devices could be synchronized.

Data Acquisition System

The data acquisition system received input from the Flow meter and displayed the flow rate and time using LabView software. It was also connected to the LED indicator voltage supply, and recorded the supply voltage to the LED indicator. After each run, the data acquisition system that included a desktop computer, stored the time, flow rate, and the LED indicator supply voltage into a data file.

The data acquisition system consisted of a desktop computer; National Instrument's Field Point distributed I/O instrument and their LabVIEW software, an indicating LED indicator, a Cannon Optura Mini DV digital camera, and a TOSHIBA LF410/LF400 Flow meter/Converter assembly. The Field Point system was used to collect flow data synchronized with the LED indicator. The camera recorded the movement of the solid particles in the pipe. The computer running the LabVIEW program collected and stored the data from the Field Point system.

In order to synchronize the flow data from the computer with the video data from the camera, an LED indicator was switched on at the beginning of the test. The computer put a time

stamp on each data point as well as recording the supply voltage to the LED indicator. The camera also recorded the LED so that the frames in which the LED turned ON and/or dimmed would be referenced to the flow reading of the computer data file. In this manner elapsed time could be counted to the point at which the solid particles stopped moving at the bottom of the pipe. The flow could then be correlated to the status of the solid particle movement.

A Baldor series 15H inverter controller was used to control the speed of the pump. The controller was programmed to ramp up to maximum velocity in one minute then to ramp down to the minimum velocity in 10 minutes. In this way the exact flow rate at which the solid particles started to settle out could be determined dynamically by correlating computer and video data. Adjusting the deceleration of the pump motor could enhance the precision of the measurement.

C. Slurry Characteristics

This work was focused on developing a reliable and accurate method to measure what we defined here as the critical deposition velocity. The technology will eventually be utilized to study this parameter for slurries that contain more than one solid species, and when those species have a wide range of specific gravities and different particle size distributions. Since the emphasis is on the measurement methods rather than on determining the actual critical deposition velocity for a particular radioactive waste simulant, the slurry characteristics reflected these conditions.

The slurry was formed by mixing measured amounts of both clean tap water and pink Garnet particles. We selected the Garnet particles because of some superior mechanical properties that would facilitate the measurements and enhance their accuracy. These include:

- Distinctive color that was easy to visualize after washing to remove sub-micron deposits.
- High specific gravity that enhanced settling even at high mixture velocities.
- Supplier offered selectable narrow particle size distribution.
- Free flowing and not agglomerating
- Most particles were spherical or ellipsoidal, few were angular.

Garnet particles when received were covered with a thin layer of very fine powder. When mixed with water, the fine particles washed in it and caused it to become cloudy and opaque. Since visual observation of the settled particles was essential to the success of this experiment, the Garnet particles had to be batch washed and decanted several times (usually six times) until the washing liquid became satisfactorily clear.

The physical properties of the Garnet particles were obtained after they had been washed and left to dry on a large flat surface for several days. Material and bulk densities, void fraction, average settling velocity and the particle size distribution were measured and are given below:

Material Density	= 3.40 gm/cc
Bulk Density	= 2.04 gm/cc
Void Fraction (After Washing)	= 0.40
Average Settling Velocity	= 0.01 – 0.02 m/s

Particle Size Distribution = 50 μm ≤ 24% ≤ 75 μm
75 μm ≤ 68% ≤ 125 μm
125 μm ≤ 8% ≤ 150 μm

The particles had mostly spherical or ellipsoidal shapes, but a few were angular. The mean particle size was taken to be 100 μm. In this experiment, slurries of 10%, 20%, and 30% solids by volume were tested

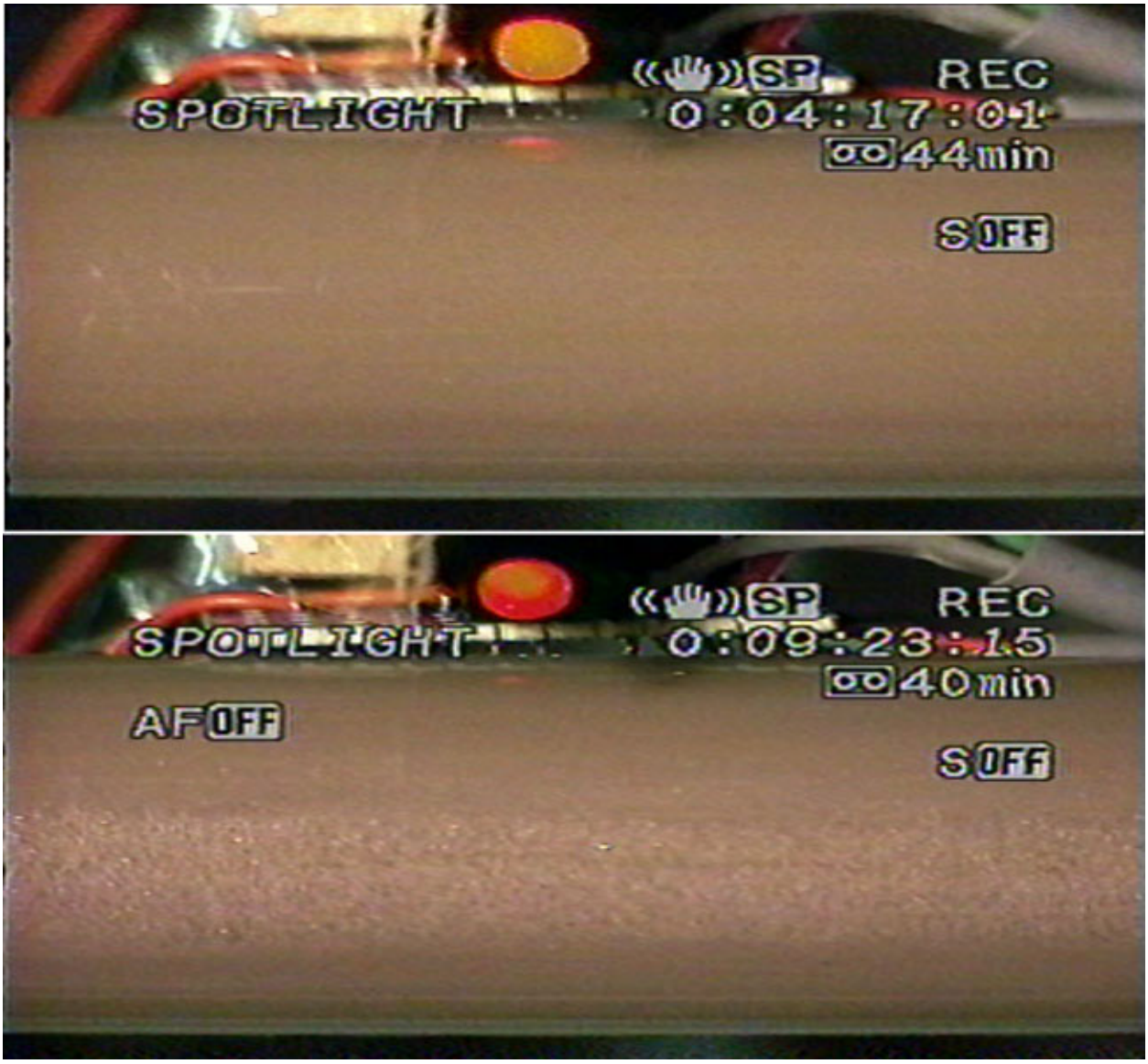

Figure 3. Captured Images During "Homogeneous" (Upper Photo) and "Settled Bed" (Lower Photo) Flow Conditions

4. DATA

The experimental data was contained in a file created by the LabView program, and on the recorded tape in the digital camera. The two files are synchronized by matching the time on each data record that corresponded to the switching off of the LED indicator. Once that step had been done, then, the flow rate, obtained from the recorded output of the flow meter, read at the same elapsed time as that registered on the digital camera recording when the settled solids stopped moving, is found. That flow rate when divided by the pipe's cross-sectional area produced the critical deposition velocity as defined in this work. The same process was repeated for all the test runs.

The data from the LabView program can be represented as a graph showing the variations of the flow rate vs. time during the deceleration sequence. During that period two events took place the first is when the LED indicator is dimmed and the second is when the moving bed of solid particles along the pipe's bottom stop moving. Figure 3 show two photographs taken from the digital camera record, one shows the solids moving at a relatively high speed as a homogeneous slurry, and, the second shows the solids bed becoming stationary and forming a settled bed. Figure 4, taken from the LabView program, gives a graphical representation of the flow rate vs. time during the deceleration sequence in the first run with the 10% slurry volume concentration. Note that the point at which the LED dims and the moment when the stationary bed forms are labeled in the figure. These values were obtained by correlating the LabView file with the digital camera, as explained previously. The data collected corresponded to actual solids concentrations of 7.89%, 21.57%, and 30.47%. In this paper, these slurries are referred to as the 10%, 20%, and 30% slurries, respectively.

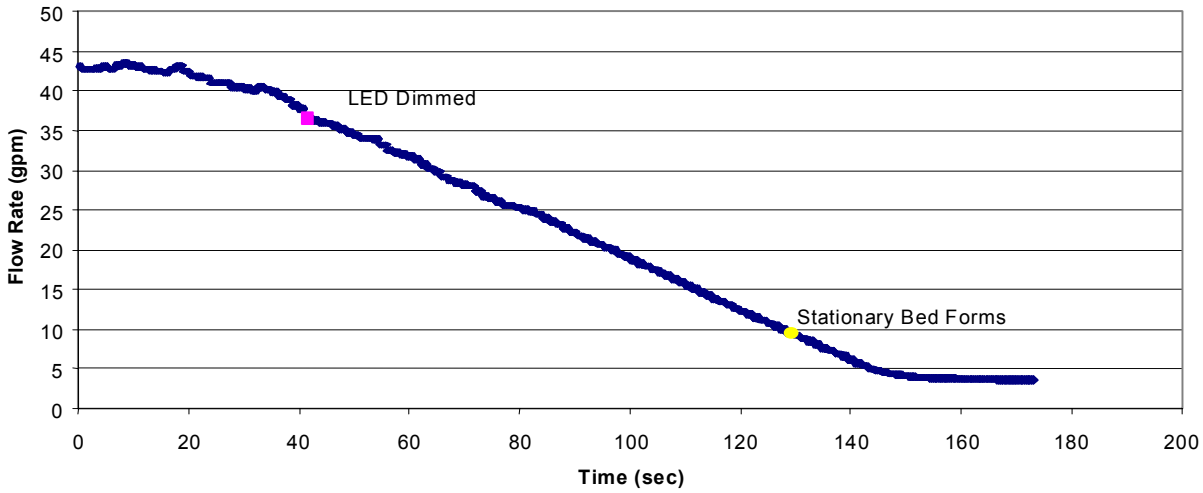

Figure 4. Typical Recorded Output From the Data Acquisition System

Figure 5 presents a summary of the data obtained in this study. Clearly the critical deposition velocities, based on this data, appear to be lower for higher slurries with higher

volume concentrations. This is readily and reasonably explained by the increased effect of hindered settling at higher concentrations. However, such a complex phenomena must be influenced by many more parameters than just the settling velocities. Much more data needs to be gathered to draw concrete and accurate conclusions about the physics of this phenomenon.

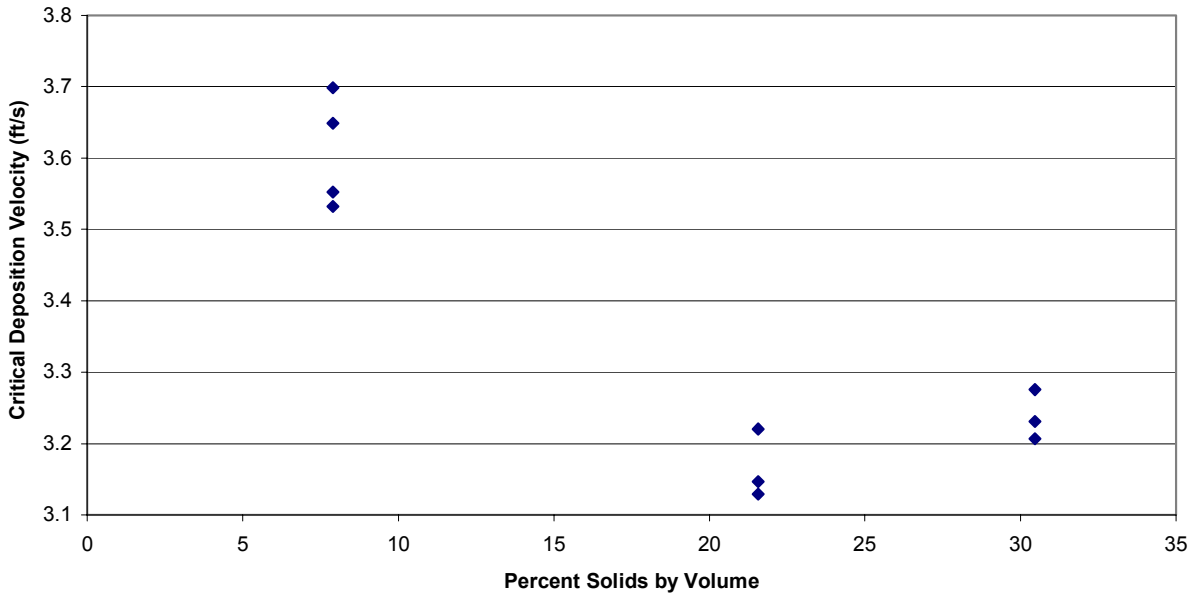

Figure 5. Variations of the Critical Deposition Velocity with the Slurry Volume Concentration

5. CONCLUSIONS AND FUTURE PLANS

A measurement method to determine the Critical Deposition Velocity of slurry made up of water and fine Garnet solids has been developed. The method appears to be reliable, and the data reproducible and as accurate as the used instrumentation. During the course of the experimental program several ideas on how to improve the accuracy of the measurement have been advanced including more precise flow measurement devices, more automated data acquisition and data reduction operations and an increased test time by slowing the rate of velocity decrease (deceleration). The data indicate that the CDV is a function of the slurry volume concentration and may be influenced by the hindered settling as well as the turbulence damping that result from such high volume concentrations. However, many more tests at varying conditions are needed to establish a clear understanding of the factors that influence this useful design and operational parameter for slurry transfer lines. Furthermore, additional understanding may be obtained by observing not only the moment of stoppage of a moving bed in slurry transport, but also the moment at which a moving bed begins to form as a prelude of the stationary bed phenomenon. This may require additional modifications to the measurement method.

We hope, in addition to improving the instrumentation system and to collecting more data at more volume concentrations, to conduct a comprehensive and systematic experimental program using two and three species slurries. This multi-species slurries will be formed with

solid particles that have widely varying specific gravities and with narrow as well as broad particle size distributions. All at large number of volume concentrations of the overall slurries and for the separate species in relation to each other. Here complications may arise if visual color discrimination of the different species is not easy to achieve. We hope to generate sufficient information from these studies to encourage and facilitate physical modeling of this useful multi-phase flow phenomenon.

6. REFERENCES

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