NUCLEAR TECHNIQUES AND CROSS-CORRELATION METHODS FOR SPECTRAL ANALYSIS IN TWO-PHASE FLOW MEASUREMENTS IN MINERAL PIPELINES

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ABSTRACT

In mineral industry is common to use water to transport pellets inside pipes. In these units, the correct measurement of flow (both solid and liquid phase) is important to guarantee a safe operation. Cross correlation flow meters are devices specially suited to be used in dual-phase flow and they are based on measure the transit time due the disturbances registered between two points, in our case gamma attenuation from radioactive sources. The emphasis of this work is the application of gamma transmission and scattering technique associated with spectral analysis methods to measure the floe of solid phase in a liquid fluid inside the pipe. The detectors and the sources are outside of the tube and are positioned 10.0 cm distant one from the other. The photons of transmission/scattering gamma radiation were registered, and a cross-correlation method was applied to measure the flow and spectral analysis was used to study the flow profile inside the pipe.

1. INTRODUCTION

Biphasic flow systems as solid-liquid are found in various fields of industry, particularly in mineral processing and dredging units. [2] The displacement of solids within pipelines is one of the processes most suitable for long distance solids transport because it is possible to be a fully automated system operating 24 hours/day, transporting large quantities of minerals with low maintenance cost. Mineral pipelines are, in general, long lines and due to decrease in hydraulic power, specials and huge equipments for pumping are needed during the whole the route. Energy consumption constitutes a substantial part of the costs in a normal pipeline...
operation pipeline, for this reason it is important to development methods and devices in order to monitor in real-time these units and contributes to reduce losses and reduce costs.

The accurate measurement of solids during transportation in a pipeline is a complex problem due to the chaotic behavior of this dual-phase system (the irregular shape/sizes of the pellets and the inhomogeneous distribution within the liquid phase) [3, 4]. Two-phase flow meters employing conventional techniques cannot always be used because in most cases, these devices are invasive and suffer wear, so they must be periodically calibrated or even replaced. This limitation does not occur when the measuring device uses gamma ray scattered as measuring signal.

Gamma densitometers are noninvasive, compact, low maintenance cost devices. They are installed on the exterior of the pipeline (do not suffer wear), and they generally use scintillators detectors and a Cs-137 gamma source. The variations in signal from the transmitted/scattered gamma ray recorded by scintillation detectors are directly proportional to the concentration of mineral pellets moving inside the pipeline [5, 6].

2. FLOW OF COARSE SLURRIES INSIDE PIPES

In a pipeline, the behavior of solid phase dispersed in the liquid phase depends on a variety of physical of factors and to know the pellets ‘profile and how it is changing during the transport is a necessity for the correct operation of the unit. In normal hydrotransport operation, a pipeline is generally installed in a horizontal plane, and a simplified model is to consider the two phases as a homogeneous mixture, but the presence of solid particulates thin or too heavy causes a change in the characteristics of the fluid and the transport process [2].

Mixed flows containing solid particles dispersed in a liquid phase cannot be treated in a simplified manner because all the particles are affected by gravity and move at different speeds. This phenomenon causes certain stratification: the drift velocity of the solids in the lower portion the duct is shorter than the speed of moving solids near the top of the duct. [7]

This stratification depends both on the physical proprieties of the pellets being transported as well as the pumping process. The following terms are employed for define the critical velocities:

- **Suspending velocity**: the velocity above which the flow is fully suspended
- **Sedimentation velocity**: velocity that demarcates the upper limit of stationary bed existence.

If stratification reaches a critical level (pellet's velocity equals the deposit velocity) sedimentation rate is achieved, and the solids begin to sediment at the bottom of the duct. If this condition is not detected and persist, it may cause complete blockage of the entire system.

In a hydraulic transport system, the transport velocity is usually set close to the critical velocity which is associated with minimum pressure loss, because this is important to determine the transport velocity and to estimate the pressure loss in order to prevent the sedimentation velocity. For this reason, the knowledge of the flow rate and the pellets'
concentration inside the pipe is fundamental to characterize and classify the flow pattern and behavior of the displacement of liquid-solid mixtures [8,9].

2.1. Flow with a Stationary Bed

When the pellets are moving at a low speed, smaller but very close to the sedimentation speed, the heavier pellets tend to move and to deposit at the bottom of pipe and to form a stationary bed. In the same way, the lighter particles are located in the upper portion of the pipe and move with a speed slightly higher. This stratification promotes a reduction in the effective volume of the duct. In some cases, this stratification increases the pressure inside the pipe, and settled solids can be churned and move as slug flow.

2.2. Flow with a Moving Bed

When the speed is slightly greater than the sedimentation velocity, heavier pellets move towards the bottom of the duct and move as dunes. The lighter pellets are carried to the top of pipe and move with higher speed. If this situation persists, the fluid will act as being made up of symmetrical portions moving with different velocities.

2.3. Fully Suspended Flow

For speeds, higher than the sedimentation velocity, all solids are suspended and are moving in a symmetrical pattern, but not necessarily uniform. This type of flow is called pseudo-homogeneous flow and can be classified in two situations:

- Pseudo-homogeneous suspension flow: all the solids are uniformly distributed inside the pipe, and the pellets usually are moving with very high speeds;

- Heterogeneous suspension flow, when differences in pellet’s weight cause a gradient in density of the fluid (perpendicular to the pipe axis), lighter pellets are on the top of the duct and the heaviest on the bottom.

3. PIPE FLOW MEASUREMNTS USING GAMMA DENSITOMETRY

Gamma densitometry technique is one of the best suited for measuring the flow profile in pipelines. Using a gamma, we can measure the pellets’ distribution inside the pipe and measure the velocities. [6]

A sealed gamma radiation source, properly shielded, and with energy and intensity enough to penetrate and be transmitted across the pipe is positioned outside of the pipe and a NaI scintillation detector (lateral face completely shielded and front face fully exposed) is installed in the opposite side to record all the photon, transmitted and scattered by the fluid.

With this geometry three situations can affect the accuracy final results:
• uncertainty of transmission: inside the pipe, pellet's concentration is generally not symmetrical and the relationship between the pipe's diameter and the source/detector solid angle causes an uncertainty in the measured concentration of moving pellets;

• uncertainty of scattering: inclusion of photons which have been scattered outside the sensitive region and were transmitted to the visual field of the device.

• uncertainty in the response of the detectors: it occurs when very fast flows are happening, the speed of the pellets causes a sudden change in the count rate which is not recorded by the detectors.

4. POWER SPECTRUM ANALYSIS IN FREQUENCY DOMAIN

Variations in the density of the fluid moving within the pipe are strongly dependent on the transport process. Using two independent source/detector set, appropriately positioned, these changes can be registered. Techniques which correlate the statistical dependence between random signals as cross-correlation function (CCF) and power spectral analysis (PSA) can be applied to study the dynamic behavior of the pellets within the pipe. [1]

4.1. Cross-Correlation Function (CCF)

For the signal recorded by the detectors, the CCF is estimated by the equation of convolution:

\[ R_{xy}(\tau) = x(t) \otimes y(t) \]  

where:

\[ x(t) \] — gamma photons recorded at position 1
\[ y(t) \] — gamma photons recorded at position 2
\[ \tau \] — transient time

The convolution equation may be written as:

\[ R_{xy}(\tau) = F^{-1} [ F[x(t) \otimes y(t)] ] = F^{-1} [ X(S) \cdot Y(S) ] = F^{-1} [ H(S) ] \]  

Onde:

\[ X(S) \] — \[ x(t) \] Fourier Transform
\[ Y(S) \] — \[ y(t) \] Fourier Transform
\[ H(S) \] — \[ x(t) \] and \[ y(t) \] convolution Fourier Transform
\[ R_{xy}(\tau) \] — Cross-Correlation Function

The transient time between the signals recorded by detectors 1 and 2 is equal to the time in the maximum value of the FCC. One of the advantages in using the FCC to measure the transient time between two events is due to this result is independent of interferences due caused by spurious signals as electrical noise. In FCC methodology only signals that are present in real counts \[ x(t) \] \[ y(t) \] are relevant.
Usually, $\rho_{xy}$, the correlation coefficient, is used to measure the transient time, so:

$$\rho_{xy} (\tau) = \frac{R_{xy} (\tau)}{\sqrt{[R_{xx} (0)] *[R_{yy} (0)]}}$$

(3)

Onde:

$R_{xx} (0) = \chi (t)$ Auto Correlation Function in $t = 0.0$

$R_{yy} (0) = \gamma (t)$ Auto Correlation Function in $t = 0.0$

4.2 - Power Spectral Density Analysis (PSD)

Generally spectral analyses are used to inform how the energy of a signal is distributed in the frequency domain; in our case, this methodology is applied to identify flow patterns. The random fluctuations in signal due to of gamma radiation scattered by the moving pellets generate patterns, and these are used to identify a flow model.

The function $H (S)$ is the Fourier transform of the correlation curve in the frequency domain, and $H(S)$ is a complex number and can be as:

$$H (S) = X (S) * Y(S) = H_{\text{Real}} (S) + H_{\text{Img}} (S)$$

(4)

where:

$H_{\text{Real}} (S)$ - Real part of $H(S)$ no frequency domain

$H_{\text{Img}} (S)$ - Imaginary part of $H(S)$ no frequency domain

$S$ - Frequency

The Power Spectral Density (PSD) is given by:

$$\text{PSD} (S) = \frac{\sqrt{[H_{\text{Real}} (S)]^2 + [H_{\text{Img}} (S)]^2}}{N}$$

(5)

where:

$N$ - Total number of data recorded in each detector

The PSD is usually presented in the logarithmic scale, in units of decibels, dB:

$$\text{PSD} (S) \text{ dB} = 10 * \log_{10} \left( \frac{\text{PSD} (S)}{\text{PSD} (0)} \right)$$

(6)

5. NUMERICAL EXAMPLES OF SOLID FLOW MEASUREMENTS IN A PIPE

In this work, the transport of solid pellets in a pipeline was modeled considering as spherical glass particles with different sizes and moving inside a PVC pipe (inner diameter 8.5 cm). The measurement system consists in independent two sets $^{137}\text{Cs}$ gamma sources/scintillation
detectors (NaI 2"x2") with the lateral faces completely shielded with lead, and the front face exposed. These detectors were separated by 10 cm, and the internal fluid used was water.

In all studies, the pellets were moving with constant velocity and in the same direction as the liquid phase. In certain instants of time, the location of each pellet was calculated and the count rate in the detectors was estimated using the MCNP-X code. Using numerical interpolation the response curve of each detector NaI scintillators was generated for each flow model.

The first flow pattern studied was pseudo-homogeneous fully suspended pellets with 20, 60 and 100 pellets. In each case, the cross-correlation coefficient was calculated using equation 3 and transient time was equal the time corresponds to the maximum point of the curve.

Figure-1a shows the registry for scintillators detector at position 1. In this model, the particles move with constant velocity at 2.0 cm/s and the distance between the two detectors is 10 cm; the transient time between events must be equal to $t = 5.0$ s. In Figure-1b it can be seen that the maximum cross-correlation curve coincides with the theoretical value.

![Figure 1: Simulation of Fully suspended flow (pseudo-homogeneous) using 20 pellets with 0.75 cm of diameter and drift velocity of 2.0 cm.s$^{-1}$ (a) count rate recorded at detector 1; (b) cross-correlation coefficient; (c) PSD.](image)

The Figure-2 shows the cross-correlation coefficient for other two cases (60 and 100 pellets) for pseudo-homogeneous full suspended flow.

Both curves have the identical pattern. Between 0-10 s, the distribution is narrow this is because more pellets are moving with the same velocity and the cross-correlation function between the signals from detector D1 and D2 tends to be a more symmetric around the maximum value. After the pellets, the curve shows a plateau, $t=15.0$ to $t=60.0$, this constant value is the radiation from the source.
Figure 2: Cross-Correlation coefficient for the pseudo-homogeneous model with pellets moving at 2.0cm.s\(^{-1}\)velocity: a) 60 pellets; (b) 100 pellets.

It has also been simulated the displacement of thin solid particles (diameter 0.1 cm), Figure 3-a, moving with 2.0 cm/s and the show it, and the data were recorded with the same sampling frequency (1.0 kHz). As shown in Figure 3-b, the cross-correlation function methodology, even in this case, proved to be effective for calculating the transient time because the maximum value of the curve coincides with the value of the theoretical time transient. Using pellets with quite different size, the PSD of this model exhibits the same behavior observed in the previous model.

Figure 3 – Simulation of fully suspended flow (pseudo-homogeneous) using 20 pellets with 0.1 cm (diameter) and drift velocity of 10.0 cm.s\(^{-1}\): a) count rate recorded at detector 1; b) cross-coefficient correlation; c) PSD

In heterogeneous full suspend pellets model a certain degree of stratification exist. Inside the pipe, there are three distinct regions (pellets with slightly different sizes), with each moves in different velocities. In the model were used 100 pellets (diameters between 4 and .8 cm) moving with velocities between 4.0 and 6.0 cm/s. The data recorded by the detector 1 is in Figure 4-a and cross-correlation coefficient in Figure 4b. Figure 4c shows the power Spectral Density.
The curve 4-b shows a quite different shape compared with the curves for the previous cases. The maximum is situated at $t = 4.7\,\text{s}$ (average speed of equal $2.1\,\text{cm/s}$), but the curve has a wide distribution, losing the symmetry around the maximum value. This is due to the difference between the speeds of each of the layers in the heterogeneous flow: as the bottom is the layer containing the majority of the pellets and is also the slower one, the enlargement of the cross-correlation curve in a positive direction of time is due to the presence of this greater number of pellets.

For the moving bed model, 100 pellets were considered are traveling $2.0\,\text{cm/s}$ and the bed moves with $0.3\,\text{cm/s}$. In the model was considered the presence of only a single dune.

For detector 1, Figure 5b shows clearly the registry for the moving pellets, a block of peaks between $t=0$ and $t=10.0\,\text{s}$, followed by the dune movement between $t=15\,\text{s}$ and $t=50\,\text{s}$. The displacement of the dune is noticed for temporal changes in count rate slower compared to the pellets.

The cross-correlation coefficient, Figure 5 b shows peaks due to a distribution of pellets moving within the pipe, with a maximum value around $t = 4.9\,\text{s}$ resulting in an average speed equal $2.1\,\text{cm/s}$. Following this peaks the curve shows increasing pattern, but soft, due to the slow movement of the dune in the pipe. The transient time is calculated as being equal to $37.5\,\text{s}$ (average speed of the dune equal $0.27\,\text{cm/s}$).
For the stationary bed flow model, again 100 pellets with an average size around 0.8cm were moving with constant speed equal 2.0 cm/s and the dune remains motionless. In this case, there is a reduction in the space inside the pipe for movement of the pellets and Figure 6-a shows the curve for detector 1. It is clearly in the curve the movement, in block, for the pellets between $t = 0.0$ and $t = 10.0$ and followed by a region where the count rate is practically constant due to stationary dune.

In figure 6-b, the cross-correlation curve shows three distinct regions, the first one between $t = 0.0$ and $t = 8.0$ s corresponding to the movement of the pellets (maximum value of $t = 4.2$ s) with an average velocity of 2.5 cm/s. This value is greater than the theoretical value (equal to 2.0cm/s). The reduction in the space inside the pipe forces the pellets to move with higher speed. The curve also shows a region intermediate (between $t = 10.0$ and $t = 14.5$s), with a peak with a maximum around $t = 12.24$ and a region in which impossible to identify any point of maximum (region between $t = 20.0$ and $t = 60.0$ s).

6. CONCLUSIONS

We describe cross-correlation and spectral techniques to get information about bi-phase (solid/liquid) moving inside a pipe. The results demonstrated a significant advantage in use cross-correlation from signals registered by two scintillators detectors to measure transient time and study the flow of solid pellets moving inside a pipe: cross-correlation function measures the signals from gamma attenuation by the pellets and rejects both signals from electrical noise or signals from spurious gamma scattered by the system.

The curves can be used to identify different flow patterns, which usually occur inside the pipe but more efforts have to be done to study the effect of sensor separation and time intervals specially for measure fast flow rates.

REFERENCES