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Sand rate model and data processing method for non-intrusive ultrasonic sand monitoring in flow pipeline

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ABSTRACT

Sand production is a critical issue during oil and gas production from sandstone reservoirs. Uncontrolled sand production not only poses the risk of well failure, but also can cause extensive damage to surface and subsurface facilities such as tubing, pumps, valves and pipelines. In recent decades, research on sand production has been conducted in several fronts including sanding prediction, sand monitoring, sand control and well-bore integrity analysis to prevent or alleviate sand production and its consequences. This paper mainly focuses on sand monitoring based on non-intrusive ultrasonic sensor which produces real-time information that can be used for maximizing the safe production of hydrocarbon.

We used non-intrusive ultrasonic sensor to monitor the acoustic signals generated by sand particles impacting the pipe wall, and developed a methodology for processing acoustic signals based on the kinetic energy of sand particles in the pipeline. Further, we developed a procedure for identifying and filtering acoustic noise from unrelated events. We validated the proposed methodology for signal processing against experimental data. The results indicated that the de-noising algorithm could filter out the noise from the acoustic data and the model was effective for assessing the sand rate.

1. Introduction

The ability to continuously monitor sand in the flow is extremely useful to petroleum engineers. The information can be used for minimizing erosion damage to the production facilities, avoiding the wellbore collapse, preventing equipment (pipeline and valves) damage, predicting sand production trends, and providing timely information for sand management measures (Sampson et al., 2002). A number of different types of sand monitoring techniques are used in the oil and gas industry. The most common sand monitors include Electrical Resistance (ER) probes and acoustic sand monitors. The latter includes acoustic probes and non-intrusive acoustic sensors (Nabipour et al., 2012).

Electrical Resistance probes detect sand by means of monitoring the degree of erosion on a probe inserted in the flow stream. The probes are made from a thin metal film as the sensing elements. The thickness of the probe is reduced due to erosion by the sand particles in the flow stream. By measuring the electrical resistance of the sensing element over time, the amount of thickness reduction of the element can be determined. Empirical equations are used to relate the loss of element wall thickness to the amount of produced sand (Nabipour et al., 2012). This type of sand monitors is not used at low sand velocities or concentrations. Further, while the method can provide a reasonable assessment of the cumulative mass of sand production, it is not effective in providing the real-time or instantaneous indication of sand production (Brandal et al., 2010).

Ultrasonic sensor is another intrusive sensor that consists of a piezoelectric transducer and a thin-walled tube coated by titanium-carbide and filled with a light mineral oil. The probe responds to entrained solids and produces an output pulse signal. The output is proportional to the kinetic energy of the striking sand, which can be related to the solid concentration (Nabipour et al., 2012). The ultrasonic sensor works best at high flow velocities, which are usually found in gas wells. Their use is not recommended at velocities lower than 5 m/s (Mullins et al., 1974).

Non-intrusive methods involve “listening” the sound generated by sand particles impacting the pipe wall (Allahar, 2003). Non-intrusive acoustic sensors are attached to the outside of a pipeline. To maximize signal detection, non-intrusive acoustic sensors should be installed about two-pipe diameter after pipe elbows (Haugen et al., 1995). Fig. 1 shows the working principle and location of non-intrusive sand sensors (Emiliani et al., 2011). They

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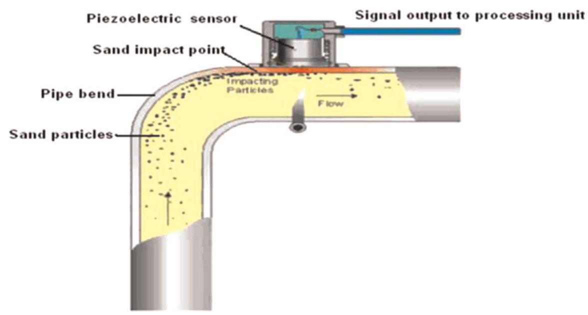

Fig. 1. Passive non-intrusive ultrasonic sand sensor (Emiliani et al., 2011).

can provide real-time sanding information and allow building an early warning system for any increased sanding activities (Nabipour et al., 2012). Non- intrusive acoustic sand monitors are also able to detect far lower sand concentrations than the intrusive types (Allahar, 2003). This sand monitoring system based on non-intrusive ultrasonic sensor has been commercially available in light oil and gas production (Brown, 1997), but it is not found the available case in heavy oil production.

In addition to the ultrasonic signals that are generated by the impact of sand particles on the pipeline wall, non-intrusive sand sensors also detect background noise that is produced by the flow turbulence, and the impact of gas bubbles or liquid droplets on the pipe wall (Shiraz et al., 2000). Additionally, the pre-processing circuit in the sand acoustic sensor and analog-to-digital conversion circuit can generate electrical noise. Generally, noise signals should be filtered before interpreting the ultrasonic signals.

Theoretically, any sand particles in the flow stream should produce an acoustic signal above the background noise level. The signal characteristics depend on various parameters such as the sand concentration in the flow stream, size and angularity of the sand particles, the velocities of sands impinging on the pipe wall, the fluid flow properties (flow regime, velocity, viscosity), and the pipe geometry. Eq. (1) presents an existing formula for calculating the sand rate using the data from non-intrusive acoustic sensors (Ibrahim and Haugsdal, 2008; Lazarus et al., 2005; Sampson et al., 2002):

$$\mathrm{SandRate} = \left(\frac{\mathrm{Signal} - \mathrm{Zero}}{\mathrm{Step}}\right)^{\mathrm{trend}} \tag{1}$$

where Signal is the raw output from the sand sensor, Zero is the background noise, and Step and trend are experimentally determined factors which are sensitive to the flow velocity, and sand particles size. The values of Step and trend are obtained from calibration work (Ibrahim and Haugsdal, 2008).

The validity of Eq. (1) has been questioned because the calibration is related to the flow attributes and must be renewed as the flow conditions change (Oudeman, 1992). Further, the processed signal is not the output voltage of the piezoelectric crystal. Instead, it is the Root Mean Square (RMS) value of the crystal output. Another equation for calculating the sand mass rate was proposed by Sampson et al. (2002):

$$\left(S_{\mathrm{pRMS}}^2 - S_{\mathrm{bRMS}}^2\right)^{\frac{1}{2}} = C\sqrt{m_t}\left(\frac{1}{2}mv^2\right) \tag{2}$$

where S_{pRMS} is the RMS value of raw output, S_{bRMS} is the RMS value of background noise, m_t is the sanding mass rate, C is a calibration constant, m is the representative particle mass that can be found by calculating a representative particle diameter, assuming spherical particles and the density of the sand, and v is the representative particle impact velocity that is obtained from a multiphase erosion model (McLaury, 1993).

To use Eq. (2), the particle mass and velocity must be known. Although the method for finding the mass and velocity of sand particles has been specified, it is difficult to measure the accurate value for the size of sand particles and track the impact velocity of sand particles (McLaury, 1993). Therefore, to simplify the procedures for calculating the sand rate from Eq. (2), it has been assumed that all particles have the same mass and velocity. However, this assumption is not realistic rendering questionable results.

In this paper, we introduce a model that relaxes the assumptions of uniform sand grains and impact energy and considers the influence of the noise on the calculated sand rate(Sampson, 2001). Actually we used our own non-intrusive ultrasonic sensor and acoustic signal processing system to perform several laboratory tests to validate the proposed model.

2. Sand rate model derivation

The model relates the sand rate to the acoustic signal generated by sand impacting the pipe wall. The assumptions used in the model formulation include:

(1) During the time of observation (Δt), the in-situ volume rate of fluid flow (Q) is constant and the velocity of solids in the pipe is $v = Q/A$, where A is the cross-sectional area of the pipe on which the sensor is installed.
(2) There is sufficient mixing of fluids and sand particles, which allows the assumptions of uniform sand concentration in the flowing fluid. Assuming all sand particles impact the pipe wall, the mass rate of sand particles passing the pipe elbow is defined as:

$$m_t = M/\Delta t \tag{3}$$

xwhere M is the total mass of solids passing the pipe elbow during the observation time Δt.
(3) Let m_i be the mass of the i^{th} sand particle striking the pipe elbow, and n be the number of sand particles striking the pipe elbow during the observation time Δt. Depending on the number of sand particles impacting the pipe wall, the mass rate of sand passing the elbow of the pipe is proportional to m_t:

$$\sum_{i=1}^{n} m_i/\Delta t = km_t \tag{4}$$

where k is a constant which may not be equal to unity as not all the sand mass in the pipe may produce signals and can be detected by the sand monitors.
(4) Assume all sand particles flow at the same velocity as the fluids flow and that all fluid phases flow at the same velocities. Therefore, statistically, the sum of individual sand masses times the square of their velocities can be replaced by:

$$km_t(Q/A)^2 = km_t v^2 = \sum_{i=1}^{n} m_i v_i^2/\Delta t \tag{5}$$

where $\sum_{i=1}^{n} m_i v_i^2$ represents kinetic energy of sand particles, v_i is the velocity of the i^{th} particle, and A is the cross-sectional area of the pipe where the monitoring is taking place. In reality, there could be slippage between different fluid phases and the sand may flow at velocities smaller than the fluid phases.

Sand sensors not only detect the acoustic signals generated by the solid particles that impact the pipe wall, but also detect noise signals from other sources. In addition, sand sensors and analog-