

Monitoring Sand Transport Characteristics in Multiphase Flow in Horizontal Pipelines Using Acoustic Emission Technology

M. El-Alej, D. Mba, T. Yan, and M. Elforgani

Abstract—This paper presents an experimental investigation using Acoustic Emission (AE) technology to monitor sand transportation in multiphase flow. The investigations were undertaken on three-phase (air-water-sand) flow in a horizontal pipe where the superficial gas velocity (VSG) had a range of between 0.2ms^{-1} to 2.0ms^{-1} and superficial liquid velocity (VSL) had a range of between 0.2ms^{-1} to 1.0ms^{-1} . The experimental findings clearly show a correlation exists between AE energy levels, sand concentration, superficial gas velocity (VSG), and superficial liquid velocity (VSL).

Keywords—Acoustic Emission (AE), multiphase flow, sand monitoring, sand minimum transport condition (MTC), condition monitoring.

I. INTRODUCTION

TRANSPORT of sand particles in multiphase production and transfer systems has attracted considerable attention since the increasing amount of sand in horizontal pipelines produces a stationary sand deposit which creates pressure drops and affects the rate of production [1]. The damage caused by the sand particles depends upon several factors such as fluid properties, flow regime, pipe material properties and sand characteristics (particle velocity and the incident angle of the eroding particles) [2].

There is a need for sand monitors and/or erosion monitors in different industries such as the oil and gas production industry to provide continuous monitoring of well performance to enable alleviate or at least reduce sand production problems in multiphase flow. Sand monitoring techniques can be classified mainly as either intrusive or non-intrusive. Intrusive techniques are used inside the pipes and include erosion based on sand monitoring probe. They have the capability to supply a direct measurement of sand erosion. Non-intrusive techniques are used externally (outside the pipe), for instance acoustic sand detectors, and have advantages over the intrusive probes due to greater sensitivity, cheaper installation and the ability to be retrofitted in the most fields.

AE is defined as the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material [3]. The elastic

waves, typically in the frequency range from 25kHz to 1MHz propagate through the material and can be detected by an AE sensor [4]. Many recent publications have shown that AE technology can offer reliable quantitative information about the process being monitored [5].

AE technology was employed to monitoring sand particles in two-phase gas-sand flow system. El-Alej et al [6] demonstrated that AE technology is capable in detecting the presence of sand particles in two-phase flow. In this study, AE signals generated by two-phase gas-sand flow system with sand injection over a different range of VSG could successfully be correlated. In another study undertaken by Al-Lababidi et al [7], a correlated between AE signals and gas volume fraction and Vsg was established. Alssayh et al [8] applied the AE technology to detect the slug velocity in two-phase flow (gas-liquid).

In this research work attempts were made to evaluate the application of Acoustic Emission (AE) technology as a monitoring tool for multiphase flow in horizontal pipes. The study presents results of the use of AE for monitoring sand transport and deposition characteristics in air-water two-phase flow; this is in addition to correlating AE activity with sand concentration levels for varying VSL and VSG.

II. EXPERIMENTAL SETUP

The experimental investigation involved the assessment of concentration of sand in three phase flow (air-water-sand) in a horizontal pipe. Different VSG and VSL ranging from 0.2ms^{-1} to 2.0ms^{-1} and 0.2ms^{-1} to 1.0ms^{-1} respectively were applied.

The experimental test rig was constructed using ABS plastic (class E) pipes. The total flow length of the loop is 32m, with the inner diameter equal to 0.05m. The test section consists of a Perspex window for observation, see Figs. 1 and 2. The AE acquisition system employed piezoelectric transducer (Physical Acoustic Corporation type WD) with an operating frequency of 100kHz – 750kHz. The acoustic sensors were connected to preamplifier set at 40dB. The AE waveforms were acquired at a sampling rate of 5MHz. A detection threshold was set at 30dB, approximately 3dB the background noise, for the acquisition of traditional AE's generated from the flow.

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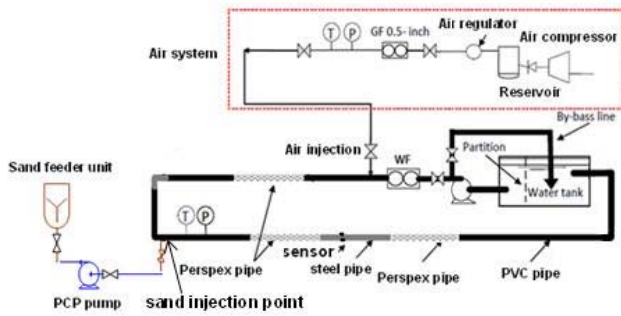
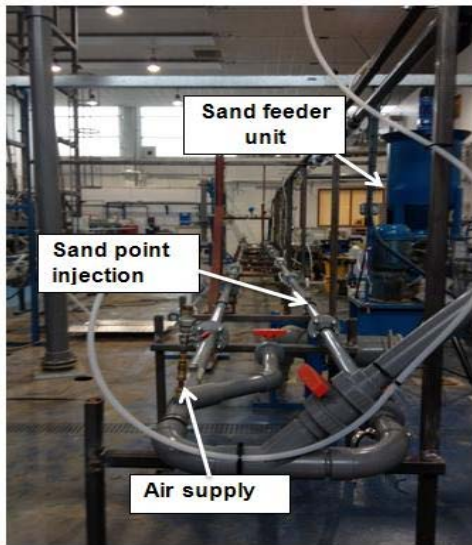
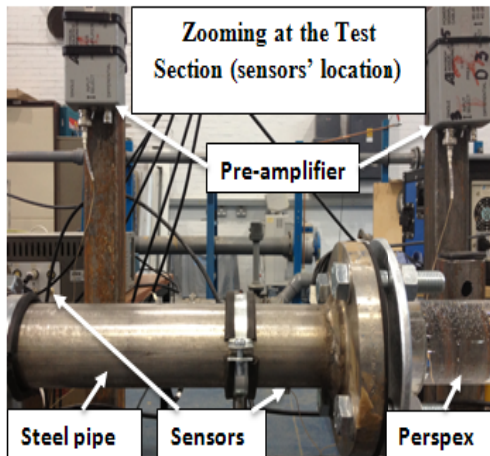


Fig. 1 Schematic diagram of Multiphase flow test facility



(a) Two-phase/three-phase test facility



(b) Test section of two-phase flow facility

Fig. 2 Multiphase test rig

Three timing parameters; the hit definition time (HDT), hit lockout time (HLT) and peak definition time (PDT) were used to acquire AE waveforms. The function of HDT is to enable

the system to determine the end of the hit, close out the measurement processes and store the measured attributes of the signal. The HLT is used to inhibit the measurement of reflections and late-arriving parts of the AE signal, so that data from wave arrivals can be acquired at a faster rate, whilst PDT is used to enable determination of the time of the true peak of the AE waveform. These parameters were set at 60000 μ s, 6000 μ s and 1000 μ s respectively.

The system was continuously set to acquire AE absolute energy (Joules) over a time constant of 10ms (milliseconds) at a sampling rate of 100Hz. The absolute energy is a measure of the true energy and is derived from the integral of the squared voltage signal divided by the reference resistance (10k-ohms) over the duration of the AE signal [9]. The following equation can be used to calculate the AE energy:

$$AE\text{-Energy} = 1/R \int_0^T v^2(t) dt \quad (1)$$

where $v(t)$ is the time dependent voltage from the AE sensor, and T the duration of the entire event over which the integration is performed. This energy is directly proportional to the electrical energy of the AE signal in the measured bandwidth by a constant of system electric impedance [10], which in this instance was 10k Ω .

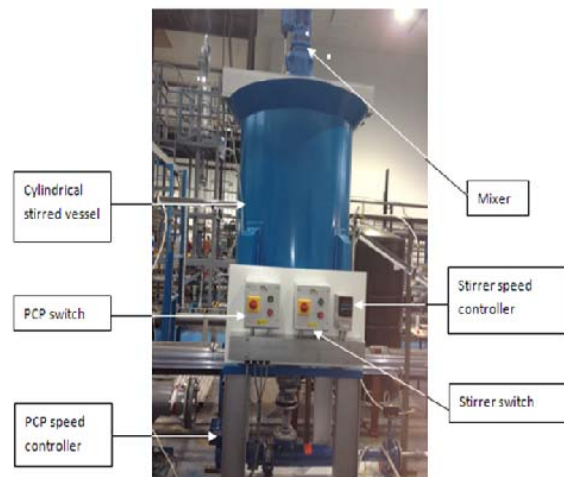


Fig. 3 Sand feeder unit

Water was circulated in the flow loop using a centrifugal pump with a maximum capacity of 40m³/hr and a maximum discharge pressure of 5barg. The water flow was metered using an electromagnetic flow meter, ABB K280/0 AS model with range of 0-20m³/hr. The water reservoir tank had a capacity of approximately 1500 litres.

A mixture feeder unit as shown in Fig. 3 was installed upstream of the test section. The mixture feeder unit consists of a cylindrical stirred vessel (800 mm diameter and 500mm high), with a 365mm diameter axial flow impeller. The mixture of sand-water was injected into the flow loop through a sand injection point installed after the water and air mixing point using variable speed progressive cavity pump (PCP)

with capacity of 5l/m and 5barg maximum discharge condition.

The mixture feeder unit created a homogeneous sand-water mixture at atmospheric conditions. The mixture was injected into the flow as dense slurry of sand at a speed of 0.126m/s using a pump. The type of sand used in the test was Congleton HST50 with an average sand particle diameter of 200 μ m, and a mixture density of 2650kg/m³. The sand concentrations studied are listed in Table I.

TABLE I
SAND IN-SITU VOLUME CONCENTRATIONS USED IN TEST

Sand concentration lb/1000bbl	Sand volume fraction (Cv)	Sand weight (g)
300	3.23E-04	505
400	4.31E-04	673
500	5.37E-04	839
600	6.46E-04	1009
700	7.54E-04	1178

lb/1000bbl = pound per 1000 barrels, Cv = sand volume fraction, g = gram.

The distribution of sand particle sizes for Congleton HST50 used in the tests is shown in Fig. 4, spreading between 50 μ m and 500 μ m.

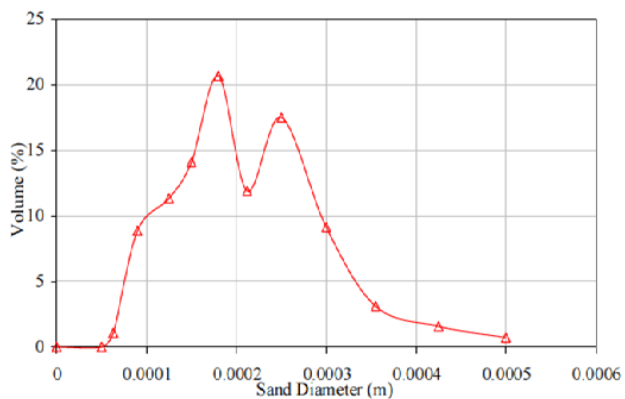


Fig. 4 Size distribution of sand particles

Air volumetric flow rate, water flow rate, line pressure, differential pressure and temperature were incorporated to read the test conditions. Prior to testing, the test was started the test rig was flushed with clean water several times and then dried with compressed air to remove sand particles in the test area.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Sand Transport Characteristic in Segregated Flow

The segregated flow is characterized by two-phase flows of liquid and gas in separate regions of the pipe while still interacting at the interface between the regions. The segregated regime is usually subdivided into stratified flow and stratified wavy flow. The transition boundary between the stratified flow and stratified wavy flow is based on the relative velocity of the two phases [11].

B. Sand Transport Characteristic in Stratified Flow

Observations showed that, stratified flow regime occurs at low superficial gas velocity (0.15ms⁻¹-0.35ms⁻¹) and superficial liquid velocity (0.15ms⁻¹-0.30ms⁻¹). The liquid flows along the bottom of the pipe and the gas along the top part of the pipe, see Figs. 5 and 6.

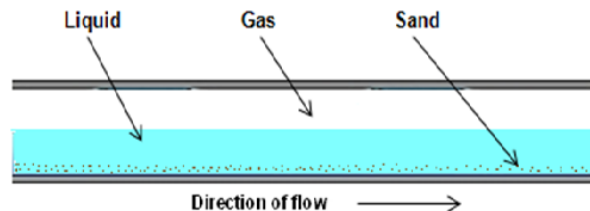


Fig. 5 Schematic sand behaviour in stratified flow regime

Fig. 6 presents the results of monitoring stratified flow regime, where relatively low AE energy levels were noted. This can be attributed to the movement of sand particles slid and creep in the film, which makes collision between the sand particles and the pipe significantly low as a result of lower VSL and VSG. It was also observed that AE energy levels increase with increasing sand concentration. The reason behind this was that the increase in the quantity of sand injected has led to an increase in the number of sand particles impacting on the pipe's walls; thereby resulting in an increase in number of elastic waves generated by the impact.

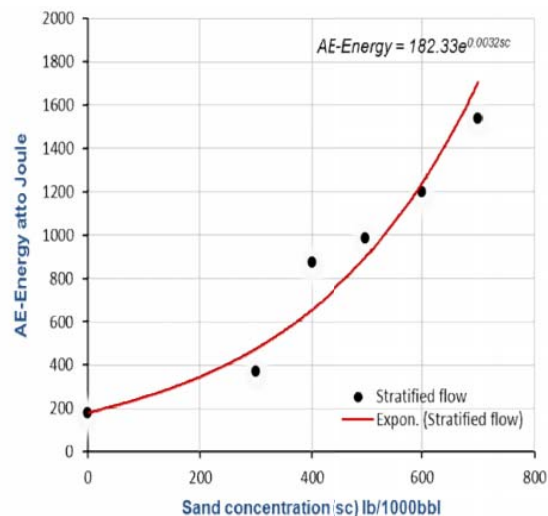


Fig. 6 AE energy levels vs. sand concentrations

C. Sand Transport Characteristic in Stratified- Wavy Flow

When higher gas velocity is applied to stratified flow, waves are produced on the gas-liquid interface constructing the wavy or stratified-wavy flow regime, and formation of ripples was observed. Further, observations showed that stratified wavy flow was observed at values of VSL (0.15ms⁻¹-0.3ms⁻¹) and VSG (0.4ms⁻¹-0.9ms⁻¹). Also noted was that the transportation of sand particles were relatively influenced by the sand concentration. At lower sand concentration, particles

were suspended within rough wave. This led to steady exchange and settlement in the film zone. As the sand concentration increased, sand particles that are located in the film zone will be dragged by the coming wave and wrap them by its movement. Fig. 7 shows schematic behaviour of sand particles in stratified wavy flow.

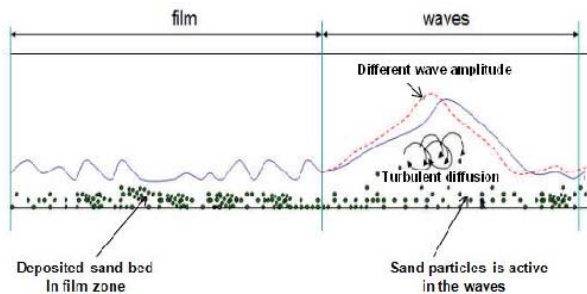


Fig. 7 Schematic sand behaviour in stratified wavy flow regime

Interestingly, it was noting that an increase in the AE energy levels were recorded as sand particles entered into waves and become active; thereby resulting enhancement of the impact energy. Further, the increase in VSG significantly accelerated the velocity of sand particles in the stream, and therefore-the probability of the hitting the steel pipe by sand particles increased with increasing VSG. This has in turn led to resulting in an increase in AE energy levels, see Fig. 8.

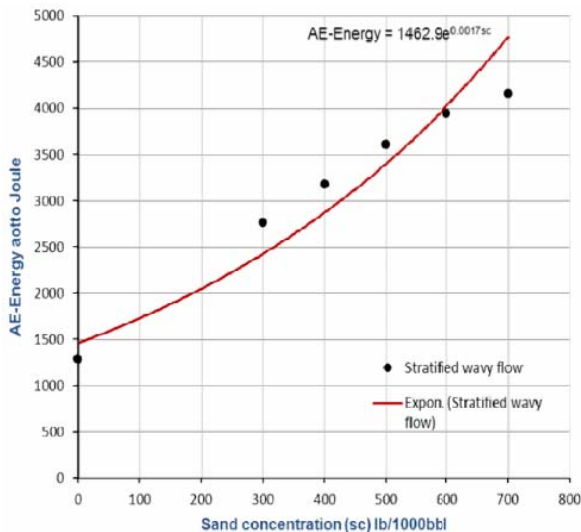


Fig. 8 AE energy levels vs. sand concentrations

D. Sand Transport Characteristic in Intermittent Flow

The intermittent flow is characterized by alternate flow of liquid and gas. The intermittent regime is usually subdivided into plug flow and slug flow. The transition boundary between the plug flow and slug flow highly depends on the quantity of the gas bubbles contained in a slug body [11].

E. Sand Transport Characteristic in Plug Flow

This is a transition regime between stratified wavy flow and

slug flow, most of the liquid flows at the bottom of the pipe, whilst the gas flows at the top. In plug flow, plug bodies of liquid fill the entire pipe cross section area, and are separated by gas pockets. Gas pockets tend to travel in the upper half of the flow pipe, and the liquid plug is free of gas bubbles or includes very few gas bubbles.

Plug flow was observed at VSL (0.95ms⁻¹-1.0ms⁻¹) and VSG of (0.1ms⁻¹-0.15ms⁻¹). In plug flow, gas pockets move along the top of the pipe having little effect upon the solid behaviour. With increasing gas velocity, the gas pocket gets deeper and the fluctuating velocities affect the sand transportation, see Fig. 9.

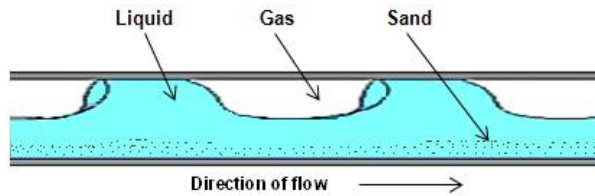


Fig. 9 Schematic sand behaviour in plug flow regime

Observations from monitoring of this flow regime indicated that the movement of sand particles in the liquid plug body eventually motivated sand particles to generate AE energy higher than that observed in the stratified wavy flow. The influence of the increase in the sand concentration on the AE energy levels is presented in Fig. 10.

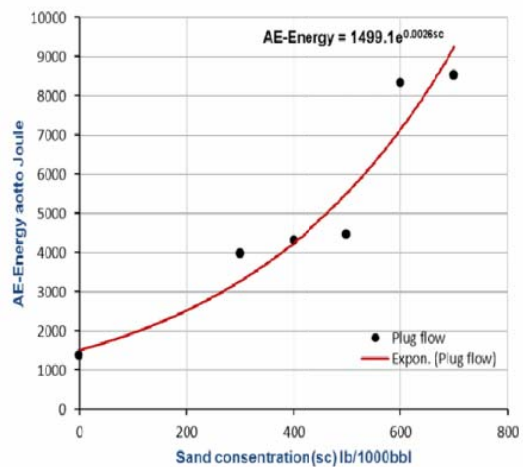


Fig. 10 AE energy levels vs. sand concentrations

F. Sand Transport Characteristic in Slug Flow

Slug flow consists of the slug body and the film or gas pocket zone. The slug flow was observed at velocity values from (V_{SL} 0.5ms⁻¹ and V_{SG} 1.0ms⁻¹). This flow regime is characterised by a formation of turbulence at the front of slug. Under different conditions of sand concentration distribution, some sand particles accommodated on the pipe wall is collected by the energy produced from the turbulent, then the sand particles is lifted into the turbulent core of the slug body. The behaviour of sand particles in slug body and film zone is

schematically shown in Fig. 11.

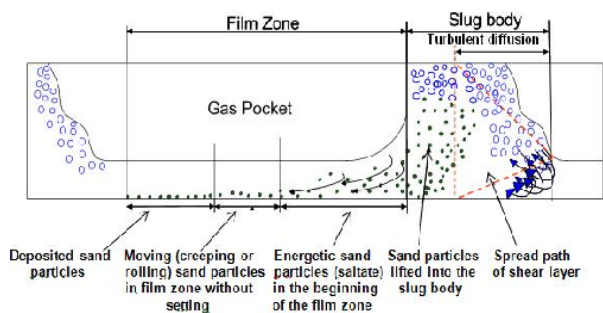


Fig. 11 Schematic sand behaviour in slug flow regime

In the case of short film zone, active sand particles move to the front, then slide, while in the case of long film zone, the particles tend to settle (length of film zone affected by consumption of kinetic energy generated by friction force). With increasing the VSG, an increase in the length of the film zone was noted. This can be attributed to values of high VSL and VSG that led sand particles to transport with the flow as they are left up by the turbulence generated at the front of slug, see Fig. 12.

It is worth noting that the relationship between the AE energy and the sand concentration in different flow regime was non-linear. It is also worth mentioning that the AE sensor recorded the highest values of AE energy in slug regime comparing to the other flow regimes, see Fig. 13.

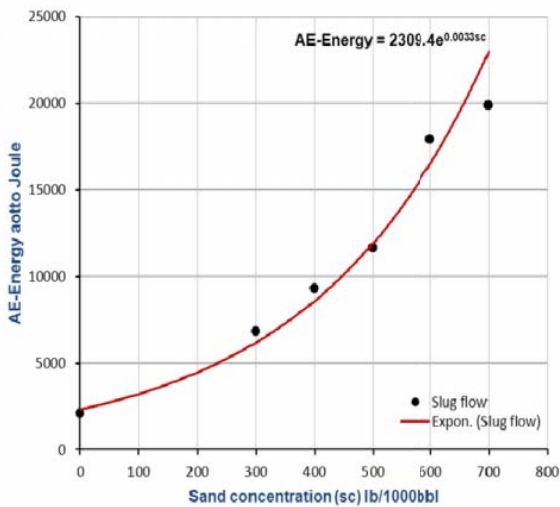


Fig. 12 AE energy levels vs. sand concentrations

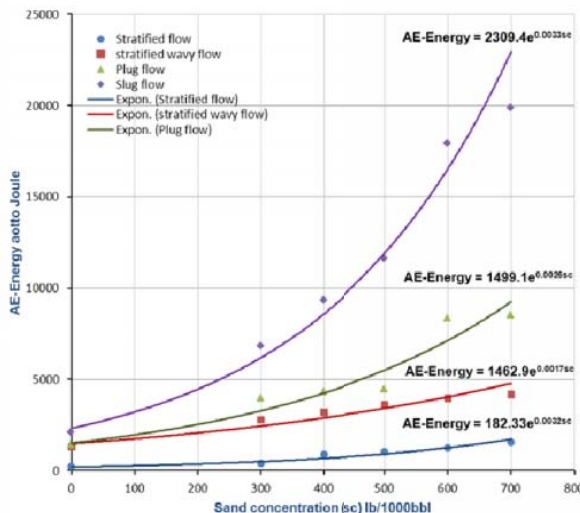
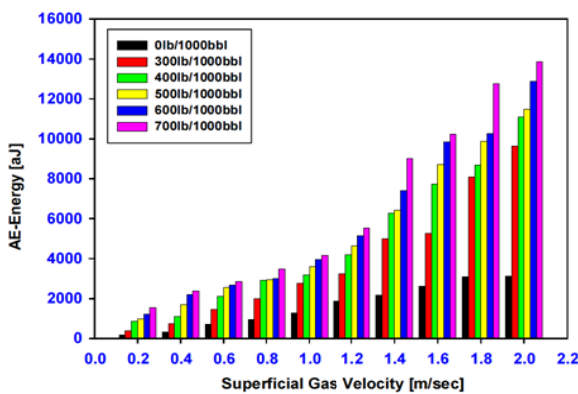


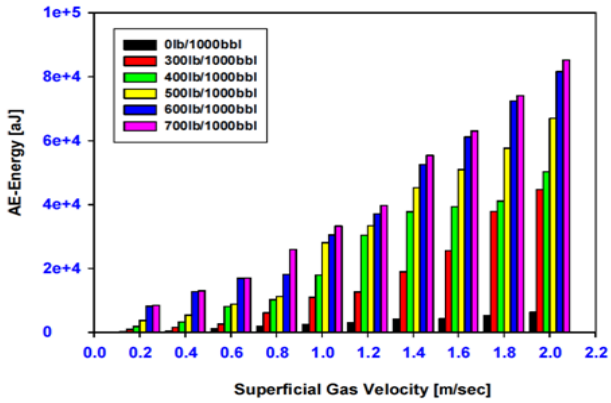
Fig. 13 AE energy levels plotted against a range of sand injections for different flow regimes

G. The Effect of Vsl, Vsg and Sand Concentration on AE Energy

Figs. 14, 15, and 16 reflect the general observations results and of the effect of the quantity of injected sand, VSL and VSG on AE trend. The results revealed that, at constant VSL an increase in AE energy was noted with increasing in the quantity of injected sand and in VSG values ranging from 0.2ms⁻¹ to 2ms⁻¹. As the amount of injected sand was kept the same and higher values of VSG and VSL were applied, the AE energy recorded high levels. The increase in the quantity of injected sand and the values of VSG has led to an increase in the number of particles hitting the pipe wall. Further, it significantly accelerated the velocity of sand particles, resulting in an increase of AE energy levels.

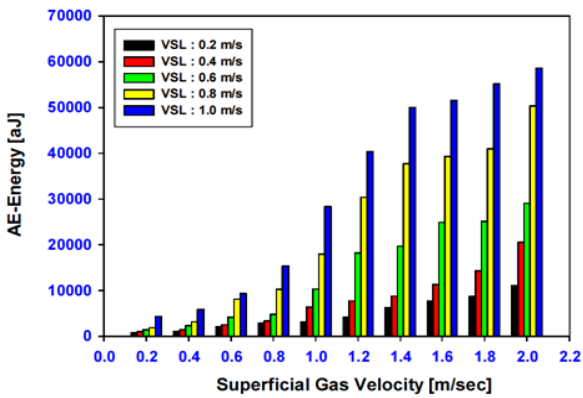


(a) VSL: 0.2 ms⁻¹

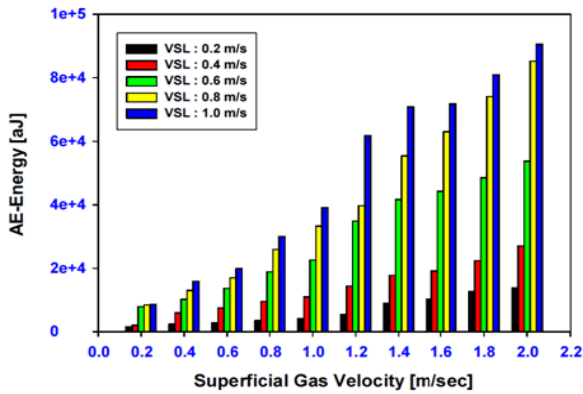


(b) VSL: 0.8 ms^{-1}

Fig. 14 AE Energy vs. Superficial Gas Velocity (VSG) for Different Sand Concentration and fixed Superficial Liquid Velocity (VSL)



(a) 400lb/1000bbi



(c) 700lb/1000bbi

Fig. 15 AE Energy vs. Superficial Gas Velocity (VSG) for Different superficial liquid velocity and fixed Sand Concentration

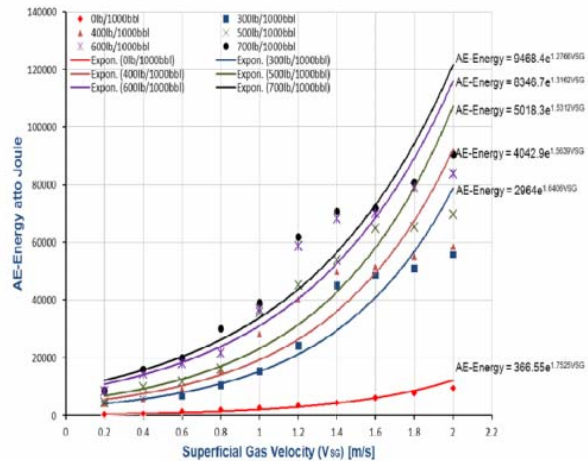


Fig. 16 AE Energy vs. Superficial Gas Velocity (VSG) for Different Sand Concentration and fixed Superficial Liquid Velocity (VSL)

H. Identification of Sand Minimum Transport Condition (MTC)

The minimum sand transport condition (MTC) is defined as the condition at which the sand particles remain suspended in the liquid (homogeneous flow) and are not deposited onto the pipe [11]. There are two ways to determine sand suspension in fluid flow. The first is based on a force balance, including lift and drag forces on a single particle. The second approach uses turbulence theory, and balances the strength of turbulent eddies necessary to entrain particles into the fluid against gravitational forces, which act to settle the particles out. For MTC the energy required for the particles not to be deposited out of the flow must be just equal to the turbulent energy effective in suspending them [12].

Results presented in Fig. 17 show the minimum sand transport velocity (V_{MTC}) as a function of sand concentration, it can be seen that there is a linear relationship between V_{MTC} and the sand concentration. Observations from experimental tests of sand-water flow in horizontal pipe showed that V_{MTC} was influenced by two main factors; superficial liquid velocity (V_{SL}) and sand concentration or sand volume fraction (C_v).

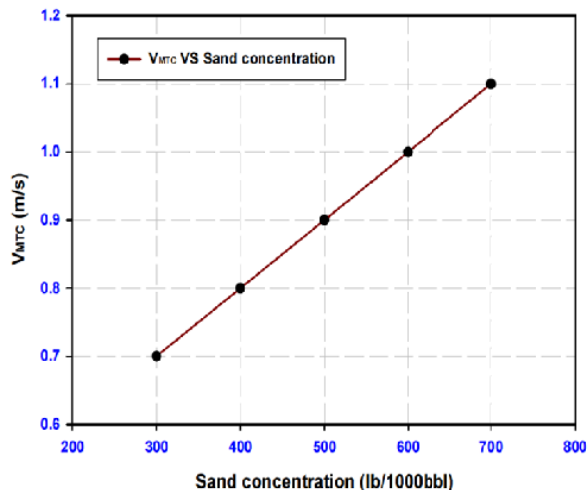


Fig. 17 VMTC (m/s) vs. sand concentration (lb/1000bbl)

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