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Laboratory Investigation of P and S Wave Types on Vibroseis EOR Technology for Low Permeability Reservoir

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Abstract. Advanced technology, specifically EOR, is needed because the reservoir still contains large amount of oil after the current oil is drained. Vibroseis EOR is one of the promising technologies under development. In its implementation, the attenuation of the S wave is lower than the P wave, so using the S wave as a vibration source will have a greater effect than using the P wave in increasing the oil recovery factor. Previous laboratory studies using circular mode vibration stimulation (S waves) revealed an increase in oil RF, porosity, and permeability as well as a decrease in Sor. The research objectives of increasing the recovery factor using both the vibroseismic method and water injection simultaneously are to explain the effect of transverse and longitudinal waves on vibroseismic and recovery factor (Sor) and also to evaluate the efficiency of water injection under the influence of transverse and longitudinal waves.
According to this research, P-wave has a greater effect on increasing oil recovery than S-wave in low permeability. This experiment used a synthetic core with low to medium permeability at a frequency of 15 Hz and amplitudes of 0.1 µm for the P-wave and 0.2 µm for the S-wave. The Recovery Factor (RF) increment reached 8.3% on low permeability (34.8 md) and 10.29% on mid permeability (115.4 md) at same amplitude for P-wave. The increase in oil RF during vibration stimulation in circular mode occurs only at mid-permeability.
This research was used in laboratory tests as well as the implementation of the EOR Vibroseis Field Trial in one of Pertamina's fields, and it was successful in increasing oil recovery in that field.

Keyword(s): axial mode, circular mode, P-wave, and S-wave.

1 Background

The increasing demand for oil and gas has stimulated the petroleum industry to conduct research that improves recovery factors, which includes the application of EOR (Enhanced Oil Recovery) methods. Viboseismic is one of the EOR methods that has been developed.
The vibroseismic method uses elastic waves as a "tool" to move reservoir rock particles, causing the fluid in the pore to move as well. The oil trapped in the pores of the rock as oil droplets will merge (coalesce) and move (figure 1). The movement of the oil droplets creates an oil stream, which increases the oil's mobility.

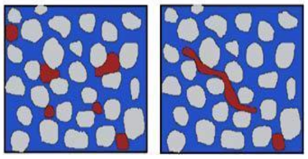

Figure 1. Oil droplets merging mechanism forming flow (Sergey A. Kostrov & Bill O. Wooden)
There have been numerous vibroseismic research results that attempt to explain the mechanism of vibration stimulation in porous media, and these results show a significant increase in oil recovery. The vibration

stimulation mechanism is still being developed to explain the phenomena that occur in both modeling and tool development. According to the results of the Beresnev[5] study, the vibration effect is proportional to the amplitude and inversely proportional to the frequency, but there is a threshold where the fluid can flow. The ineffectiveness of using high frequencies to mobilize oil trapped in capillary pipes and increasing production rate when the amplitude is also increased was explained by Wenqing Li et al[12] through their micromodel experiments, which also served as a validation of the theory.

Conventional EOR methods add energy to the trapped organic liquid while the liquid wash remains in the isolated oil. Because the pore size is so small, capillary force is the primary cause of fluid being trapped in the pores of the rock. The external force is required to break down the capillary force that carries and drains the trapped fluid. Seismic energy can be used to reach any point in porous space. In other words, the vibroseismic method has advantages over other EOR methods in terms of deeper sweeping coverage, relatively low cost, ease of application, and environmental friendliness.

The purpose of this research was to explain the transverse waves (S waves; circular mode) and longitudinal waves (P waves; axial mode) that contribute to the vibroseismic and recovery factor (Sor decrease). This research will also explain the mechanism that occurs when vibration and water injection are performed concurrently.

2 Elastic Waves

An elastic wave is a wave that travels through an elastic medium. Vibroseis EOR is a new EOR and IOR method that utilizes wave energy generated by the source and propagates through the earth's medium (rock/earth is an elastic medium). Except for rocks located near seismic sources, most rocks are perfectly elastic mediums with no significant changes and are slightly deformed. Elasticity theory is concerned with the forces that cause changes in shape and size. The concepts of stress and strain explain the relationship between forces and deformation (figure 2).

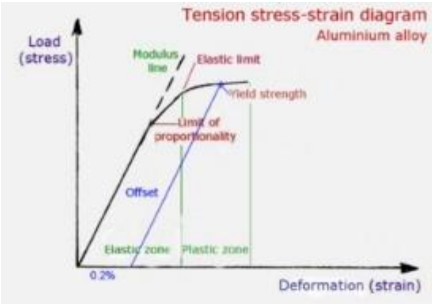

Figure 2. The relationship between stress and strain

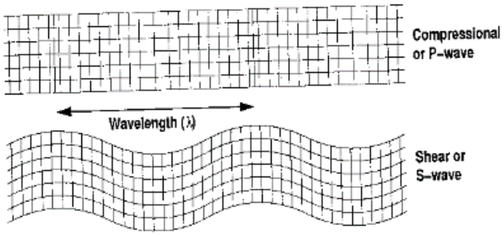

Figure 3. Movement of P and S wave particles

The speed of mechanical wave propagation in a solid medium is determined by the source frequency, material characteristics, and environmental conditions. Every rigid body has its own frequency and harmonics, which are determined by material characteristics such as elasticity, molecular density, porosity, and so on. We can assume that the resulting wave source has a broad frequency spectrum because the wave source in this tool must be a mechanical pulse (impulsive) based on the characteristics of these materials (figure 3). The generated waves can take the form of P waves (pressure) or S waves (shear).

3 Vibration Effect on Porous Media

Recent research results indicate that the optimum frequency for vibroseis EOR will be at low frequencies. The optimal frequency for vibration stimulation is low frequency because the wavelength (λ) is inversely proportional to the frequency. Low frequency is also the self-frequency of the medium (rocks) being propagated where the earth/rock acts as a low-pass filter and low frequencies have a long wave length, allowing them to reach deep reservoirs.

Capillary Pressure Effect

Capillary pressure is defined as

$$P_c = \frac{2\,\sigma \cos\theta}{r} \qquad (1)$$

The capillary pressure increases as the radius decreases. As a result, pushing the fluid through the smaller pores requires more force. To flow the fluid, additional external power of ΔP is required, as illustrated in Figure 4.

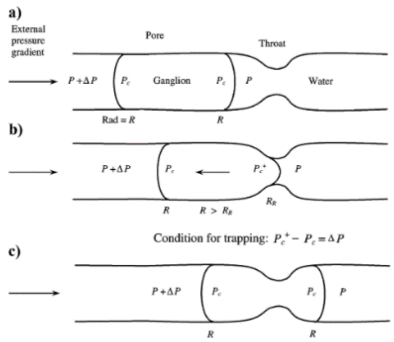

Figure 4. Microscopic review of the flow of immisible two-phase fluid through smaller pores (pore throat).

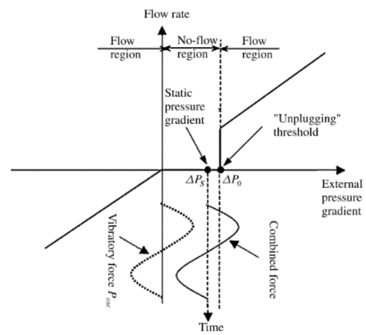

Figure 5. Wave energy (dotted line wave) accumulates (thick line wave) to exceed ΔP_0 and begins to flow (Wen qing Liet al, 2005)

Vibration stimulation creates an additional force of ΔP (external), allowing the trapped oil to move. Vibration stimulation produces this external force. This force will build up (storage concept) until it exceeds ΔP_0. Figure 5 illustrates the additional external force caused by vibration.

Liquid-solid contact angle

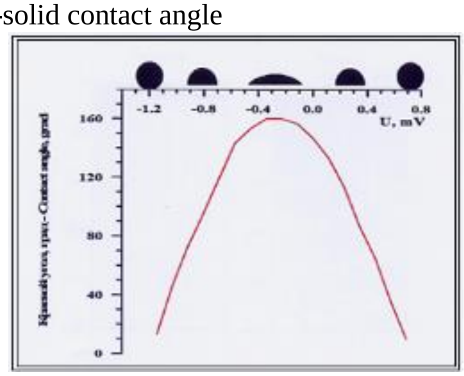

Figure 6. Changes in the contact angle of liquid-solid (Summ, Goruynov, 1976)

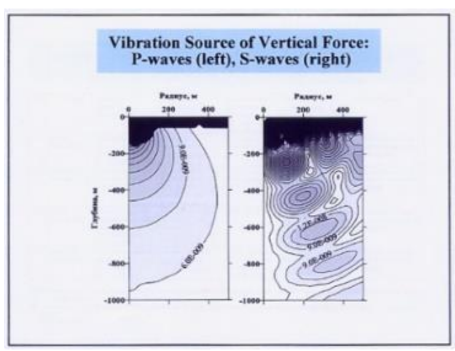

Figure 7. Attenuation of P and S waves from the source point to depth (Barabanov)

Wave energy that reaches the medium will cause the particles to vibrate. As a result, the oil that adheres to the rock pores will lose its stability. Figure 6 shows the relationship between the electric potential and the liquid-solid contact angle. Because the capillary pressure is directly proportional to the cosine of the angle, capillary pressure decreases as the angle increases. This facilitates the release of oil droplets from the pores of the rock. Wave attenuation is a problem in the field application of vibration stimulation. The earth, a low escaped tapis, is a very high medium that absorbs wave energy, particularly because the weathered layer is very thick (figure 7).

4 Laboratory Equipment

In this experiment, the axial and circular vibration modes were simultaneously vibrated with a waterflood on a synthetic core with varying permeability (k) and porosity. The frequency used is 15 Hz at the same amplitude (0.2 μm for S-wave and 0.1 μm for P-wave). Using oil & water field samples (table 1 & 2), the injection rate is constant at 0.3 cc/min until no more oil is produced. The same core samples were used before and after vibration stimulation to compare the effects (table 3 & 4).

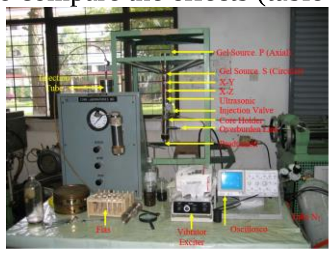

Figure 8. Vibroseis EOR laboratory equipment to stimulate the vibration of axial (longitudinal, P waves) and circular (transverses, S waves)

5 Data Analysis

5.1 5.1 Vibration Stimulation of Axial Mode

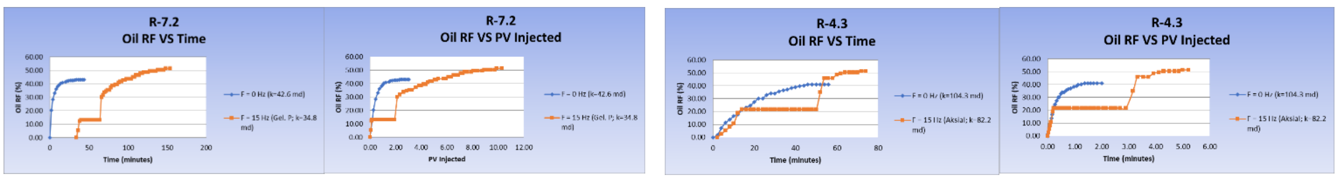

Figure 9. RF profile of oil vs time and PV injection of R-7.2 (left) & R-4.3 (right) samples before (blue) and after vibration (red)

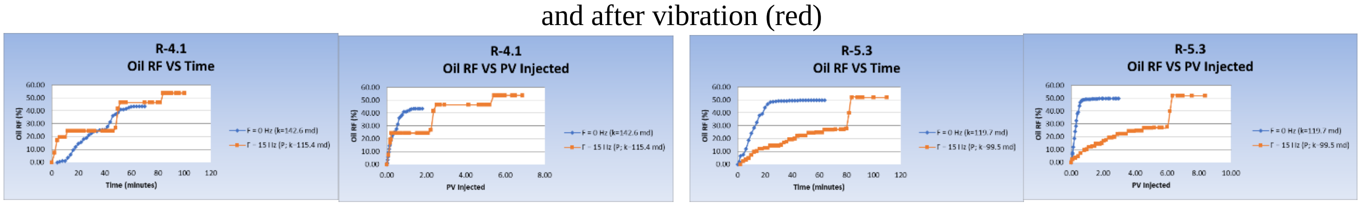

Figure 10. RF profile of the oil vs the time and PV injection of the R-4.1 (left) & R-5.3 (right) samples before (blue) and after vibration (red)

The flow rate profile shows that the vibration effect appears after a certain amount of time. The length of time (table 5) required for the vibration effect to work is determined by the sample's permeability. Sample R-7.2 takes longer time than samples R-4.3, R-5.3, and R-4.1 (figure 9 and 10). This can be explained by the low permeability of the pores or the formation of a pore throat in the rock, which requires an external force accumulation greater than the oscillating force to exceed the threshold.

This is explained by the capillary pressure effect, which states that capillary pressure is inversely proportional to the radius. The capillary pressure in the pores increases with decreasing radius. The accumulated energy of the wave to exceed the capillary pressure will accumulate longer for the same amplitude at a smaller pore radius.

The increase in RF oil compared to without vibration is higher if the PV (pore volume) injected is between 2.5-6.5 PV, according to oil production observations (figure 11). Table 6 shows a tendency for the permeability to decrease as more water is injected so that the RF vibration exceeds the RF without vibration.

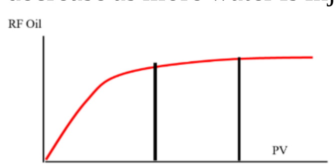

Figure 11. PV injection is required to achieve higher vibration RF than without vibration

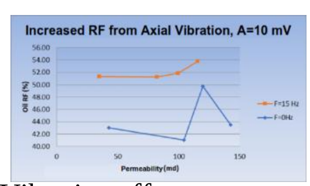

Figure 12. Vibration effect on permeability at the same amplitude (0.1 μm)

The increase in RF oil in some core samples showed an increase in the greater permeability (figure 12). At the lower permeability, it is seen that there is no increase in the same vibration amplitude. It is necessary to increase the amplitude at lower permeability in order to achieve a greater increment in RF oil.

5.2 Vibration Stimulation from Circular

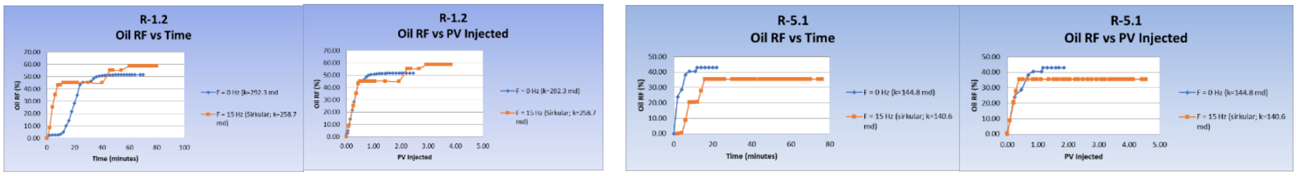

Figure 13. RF profile of oil vs time and PV injection of R-1.2 (left) & R-5.1 (right) samples before vibration (blue) and after vibration (red) circular mode

Figures 13 shows the differences in RF oil. The effect of vibration on the core sample R-1.2 (k=258.7 mD) gave an increase in oil RF while in the core sample R-5.1 vibration stimulation gave a negative effect as indicated by a decrease in the RF oil before vibration. This demonstrates that a 0.2 m amplitude can only increase the RF oil at a permeability greater than 258.7 mD. To provide a positive effect of RF oil on a lower permeability, the source's amplitude must be increased.

Conclusion

1. Axial mode vibration stimulation (P wave) is able to increase the optimum oil RF by 10.29% at a permeability of 115.4 mD. While the circular mode is able to increase the optimum oil RF 7.01% at a permeability of 258.7 mD
2. The 0.1 µm vibration amplitude can increase the RF oil to 53.79% at the core sample 115.4 mD and 51.31% at the core sample 34.8 mD. The smaller the permeability, the greater the energy/amplitude required.
3. The time required for the axial mode vibration to affect the permeability of 115.4 mD is 12 minutes while the permeability of 34.8 mD takes 56 minutes. The lower the permeability, the longer the time required for the vibration to start to have an effect on increasing the oil RF. There is an oil RF threshold at low permeability for the same amplitude
4. In this experiment, it takes 2.5 – 6.5 PV of injected water so that the RF of the oil with vibration is higher than the RF without vibration.

Appendices

Table 1. Measurement of field oil samples

Specific Gravity 60/60 °F	0.832843	Faction
API Garvity	38.4	°API
Density	0.8337	gr/cc
Visdynamic kositas 43.5 °C	2.52	cp
Dynamic Viscosity 50 °C	2.14	cp

Table 2. Measurement of formation water samples

Item	Density	Unit
Water formation	1.03	Gr/cc

Table 3. RF and Sor measurements of samples; vibration of the axial mode (P wave), amplitude 0.1 µm

No	*Core*	k (md)		F (%)		RF (%)		DRF (%)	Row (%)		DSor (%)
		No VS	VS	No VS	VS	No VS	VS		No VS	VS	
1	R-7.2	42.6	34.8	20.2	19.7	43.01	51.31	8.30	56.99	48.69	-8.30
2	R-4.3	104.3	82.2	24.9	22.4	41.00	51.26	10.26	59.00	48.74	-10.26
3	R-5.3	119.7	99.5	23.1	24.1	49.76	51.86	2.10	50.24	48.14	-2.10
4	R-4.1	142.6	115.4	23.5	24	43.50	53.79	10.29	56.50	46.21	-10.29

Table 4. RF and Sor measurements of samples; vibration of circular mode (S wave), amplitude 0.2 µm

No	*Core*	k (md)		f (%)		RF (%)		DRF (%)	Row (%)		DSor (%)
		No Vib	Vib	No Vib	Vib	No VS	VS		No VS	VS	
1	R-1.2	292.3	258.7	33.3	33.8	51.586	58.6	7.01	48.41	41.41	-7.01
2	R-2.1	43.5	47.7	23.3	22.9	45.129	39.4	-5.71	54.87	60.58	5.71
3	R-2.2	14.2	15.6	22.4	22.6	52.255	45.8	-6.47	47.75	54.22	6.47
4	R-5.1	144.8	140.6	22.6	24.3	42.876	35.4	-7.51	57.12	64.63	7.51

Table 5. Time for the vibration effect to start

No	*Core*	k (md)		f (%)		Vibration Duration (min)	Vibration Effect (min)
		No VS	VS	No VS	VS		
1	R-7.2	42.6	34.8	20.2	19.7	148	56
2	R-4.3	104.3	82.2	24.9	22.4	74	52
3	R-5.3	119.7	99.5	23.1	24.1	110	32
4	R-4.1	142.6	115.4	23.5	24.0	100	12

Table 6. PV injection is required to achieve higher vibration RF than without vibration

No	*Core*	k (md)		RF (%)		DRF (%)	PV inj > Base
		No VS	VS	No VS	VS		
1	R-7.2	42.626	34.8	43.012	51.31	8.3	5.34
2	R-4.3	104.26	82.2	41.002	51.26	10.26	3.32
3	R-5.3	119.75	99.5	49.763	51.86	2.101	6.35
4	R-4.1	142.63	115.4	43.497	53.79	10.29	2.52

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