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ACOUSTIC ARRAY METHODS FOR INSTRUMENTATION
OF IN SITU COAL GASIFICATION

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ACOUSTIC ARRAY METHODS FOR INSTRUMENTATION OF IN SITU COAL GASIFICATION

ABSTRACT

Geophysical and seismic signal processing are reviewed. The assumed physical properties of the coal burn front are discussed. Several ways in which acoustic arrays can be used for in situ coal gasification are presented and discussed.

INTRODUCTION

In monitoring the coal gasification process, the coal burn front is difficult to locate with precision; mapping the front either actively or passively would be useful. Acoustic arrays have been suggested as a means of locating the burn front in a passive mode by Lytle and McEvilly.¹

Some techniques used in geophysical prospecting and seismology can be adapted for use in acoustic array methods. However, the physical situation is significantly different from oil and gas exploration and earthquake monitoring. While distances involved can be kept smaller, acoustic propagation may be more complex and may have greater attenuation per foot. Also, the acoustic properties of the medium before and during the coal gasification process are not well known and could be quite complex.

GEOPHYSICAL PROSPECTING

The method most generally used for geophysical prospecting is seismic reflection. Its accuracy is exceeded only by measurements in wells.² A small explosive source sends P-waves down to interfaces of differing acoustic impedance and the waves are reflected back to a line of geophones on the surface, producing a seismic profile.

In continuous seismic profiling, geophones are placed about 50 ft apart in a straight line that may reach to 0.5 mi. The explosive source is placed at the shot point in the center of this one-dimensional array. A map of the linear region centered under the shot is obtained from the arrangement of geophones sensing the reflected waves. This profile covers an area half as long as the geophone array length (see Fig. 1a). After the data is obtained, the half of the array on one side of the shot point is placed at the far end of the remaining half, following the same straight line. Another shot is made in the center of the new array (see Fig. 1b). A continuous series of shots is made in this way.

An improved signal-to-noise ratio (SNR) can be obtained by averaging the geophone traces, resulting in a reduced noise level with only slight loss in resolution. If

Fig. 1. Continuous seismic profiling.

additional shots are permitted, it is possible to get multiple traces from a given depth point. These traces are called a common depth point (CDP) family. They can be stacked to reduced noise (i.e., waves traveling at unwanted velocities). If necessary, more sophisticated signal processing techniques, such as Wiener filtering, may be applied to make the data easier to interpret.³ When profiling over water, the multiple sound reflections off air-sea and ground-sea interfaces can complicate the records. However, properly designed filters can greatly alleviate this problem. The data can be displayed on TV monitors and processed in an interactive mode to determine the best processing methods for a given situation.⁴ R 27

Typical resolutions of about 100 ft are obtained at depths around 10,000 ft. The data is sampled at intervals of 2 to 4 msec (or $f_{\max} \approx 250$ Hz) and recorded digitally in the field for processing at a local processing center. The resolution can be greatly increased for lesser depths, as McEvilly has suggested. He has said that one can expect to get 10- to 20-ft resolution for 1000-ft depths using exploratory seismic arrays. Also, if vertical linear arrays of geophones are inserted into holes surrounding the fractured zone the distance from the array to the burn front can be reduced to approximately 100 ft. R 28

SEISMOLOGY

Unlike the active problem of seismic profiling, seismology is concerned with the passive recording of the teleseismic signals of earthquakes at distances greater than 1000 km. The P-wave signals traveling these distances go deep into the earth's interior, sometimes traversing the earth's core (PKP). These short period waves generally peak at 1 Hz. In addition to the body waves (P and S) there are lower frequency (0.04 Hz) Rayleigh and Love surface waves, that arrive later on long period instruments. The SNR problem is severe for these small signals (a few nanometers). Arrays of seismometers and complex multichannel equalization and filtering techniques are routinely used to improve the usefulness of the data. Using large seismic arrays, it is possible to narrow the beam width of this composite receiver to small cones in wavenumber space to suppress unwanted waves arriving at different azimuths or velocities from the beam direction. The beam width in velocity space is inversely proportional to the product of array diameter and frequency. Thus, resolution can be maintained at low frequencies by increasing the array diameter.

Sets of three seismic stations can be used to locate the epicenter of an earthquake. If more data is available, least square algorithms have been developed to fit the data with an epicenter of least residual. Thus, the arrays, with their low detection threshold, can put more reliable information into a location algorithm.

One of the tenets of seismology is that the number of earthquakes at a given magnitude follows a negative exponential curve, R 4

$$N(m) = \exp(b - am).$$

For example, there are ten times as many earthquakes of magnitude 3 on the Richter scale as of magnitude 4.⁵ The curve also implies that if one waits long enough, the probability of a large event's occurrence approaches one. McEvilly has suggested that the burn front in the coal gasification system acts as a source of microearthquakes. He expects that, as with the classical curve for average number of earthquakes versus earthquake magnitude, if one can wait long enough a big microfracture will occur, i.e., one big enough to triangulate and locate by use of passive array methods. Since the burn front will be moving very slowly (≈ 1 ft/day), it is entirely possible that large distinguishable microfractures can be extracted from the background rumble and used to locate the burn front.

THE COAL BURN FRONT

The acoustic properties of the coal burn front and fractured coal and shale are not known with any precision. Generally the coal and shale rubble should be lossy. Also, S-waves should experience greater attenuation and reflection than P-waves. The ash and "void" above the coal burn front probably will not propagate sound. Changes in the acoustic properties across the burn front profile (if any) are not known. To use the difference in properties of the ash and coal the burn of the coal must be nearly complete.

It has been hypothesized that the burn front may cause microseisms by heating the coal and shale.¹ The usefulness of these weak vibrations will depend greatly on their characteristics. Two possible extremes of these characteristics are discrete events in time and space which could be triangulated or a continuous noise source distributed over the burn front. The needed characteristic is decorrelation of the phenomena in both time and space on the order of the desired resolution. J. Benson of Sandia Laboratories, Albuquerque, reported recently that he had recorded acoustic activity at the U. S. Bureau of Mines coal gasification site near Hanna, Wyoming. Possible microseisms occurred at a rate of 1 to 5/min. The period of each microseism was approximately 8 msec. The noise occurred in a band from 50 to 1000 Hz. In one case he achieved a triangulation of a microseism, and its location was along the burn front. Because of poor array geometry he could not get more triangulations.

GEOPHYSICAL ARRAY PROCESSING

Array processing methods have application in monitoring the coal burn front location. In the processing of acoustic signals, an SNR improvement can be obtained by using an array of sensors instead of a single sensor. This is often done by delay-and-sum processing or beam forming. Generally, the beam width is inversely proportional to the product of array diameter and acoustic frequency. By narrowing the beam width, one can determine the velocities of arrival of incoming signals. For

close-in sources as in oil exploration, it is possible to focus the array on certain areas to determine location as well as obtain SNR improvement. This should also be true for coal burn front monitoring.

The improvement of the array over a single sensor is described by the array response function. The array response function is the wavenumber response to an infinite velocity impulsive plane-wave.

$$H(\vec{k}) = \frac{1}{N} \sum_{i=1}^N \exp j2\pi\vec{k} \cdot \vec{x}_i,$$

where $\vec{k}$ is the wavenumber vector and the $\vec{x}_i$ are the locations of the N sensors (Fig. 2). The half width is proportional to $1/D$ where D is the array diameter. The beam response function at a frequency (f) for a plane wave of velocity $v_o = (v_o, 0)$ would be the values of H (k) on a circle of radius f/v_o centered on $\vec{k} = (f/v_o, 0)$ as shown in Fig. 3. From this diagram one can obtain the beam response as a function of θ at that frequency (Fig. 4). The angle θ is the angle between the signal and the array beam. The SNR improvement is limited to a factor of N in the mean square improvement for N sensors for incoherent noise. However, if the noise sources are more directional, additional improvement can be obtained, at least in principle.

Array design for SNR improvement is generally determined by the minimum distance that leads to uncorrelated noise, and the maximum distance over which the signal is correlated (d_{max}). If the assumed planar array is placed broadside to the signal arrival, one packs the sensors into this plane at distance d_{min} until the diameter of the array reaches d_{max} . This procedure generally results in nearly maximum SNR improvement.

To design an array to maximize resolution or side lobe rejection, one would vary the array geometry to meet constraints placed on the array response function much as is done in radar.

The usefulness of acoustic techniques in the coal gasification problem depends greatly on the geometry of the array. A greater variety of geometric placements of the arrays are available than in geophysical prospecting or seismology.

One possibility is the placement of linear arrays in holes around the coal region to form a volume array which looks inward. Figure 5 illustrates such an arrangement. The array elements could be close to the presumed signal source so that a passive detection and location procedure should work. Triangulation of the microfracture location would be made on the basis of the first arriving P-waves, as these are thought to suffer the least attenuation in the medium. These waves also pass through the unburned region to the detectors unlike the waves received by the surface arrays proposed by McEvilly.

Active techniques could also be used although they would be more complex. Impulsive sources could illuminate the area beneath the burn front and the reflections could be observed. It may be necessary to modify some holes to slant under the

Fig. 2. Array response function.

Fig. 3. Determination of beam response function.

Fig. 4. Beam response function.

Fig. 5. Possible seismic array placement.

fractured coal bed. This active procedure would depend on reflection at the burn front-ash interface and might not work if the coal is not burned nearly completely.

If the burn front noise is not discrete enough to triangulate microseism array processing could still be used to obtain information. A simple beam-forming process could determine the depth of the front. Thus, if a "finger" developed (Fig. 6) where oxygen was burning through the coal to possibly consume the methane product of coal gasification,⁶ the burn front noise would show up in the deeper beams sooner than it should. A more complex processing involving higher order moments could measure the noise generated as a function of position within the coal bed. This technique depends on the cross-correlation function of the noise in time and three-dimensional space to be impulsive in nature. The resolution of the technique would depend on the cross-correlation function, the size of the burn area, the rate at which the burn front moves, and the duration and complexity of the computation.

Another possibility is the acoustic source at the burn front will be narrowband as sometimes accompanies volcanic action. In this case the vertical linear arrays could be replaced with fewer and smaller three-dimensional arrays placed similarly to the vertical linear arrays. Intersecting beams from these arrays could be used to locate the acoustic source.

The acoustic properties of the fractured coal and shale bed will have to be well known for these acoustic array methods to work accurately. The acoustic properties of a particular fractured coal and shale bed could be determined using active techniques with surface or subsurface arrays. These properties might be used to determine the proper placement and calibration of the array for burn front monitoring. They might also be used to infer some of the other physical properties of the coal and shale bed. For example, the mix of block sizes in the fractured coal should affect the dispersion and attenuation of the medium. This mix might be inferred on a statistical basis and could aid in determining the homogeneity of the permeability of the coal bed.

RECOMMENDATION

We suggest a two-part effort in acoustic instrumentation. First, the general properties of the acoustic media should be measured to determine the nature and order of magnitude of the various noise sources. This should be carried out in the 50 to 1000 Hz bandwidth using suitable instruments. The signals should be sampled at least twice per millisecond.

We should try to obtain data from the Hanna site to analyze its properties. For example, if all important sources of noise other than the burn-front microfractures can be located or otherwise accounted for, it may be possible to infer that microfractures have been recorded and located. This information could then be used to design subsequent experiments in instrumenting coal gasification.

Second, the dependence of several instrumentation systems on acoustic properties should be analytically appraised. Possible techniques should include both active and

Fig. 6. Unstable burn front.

passive methods of determining the burn-front location. The performance of such techniques will depend on such properties as the dispersion and attenuation of the acoustic signals. The limiting values of those properties that yield satisfactory performance of the instrumentation system should be determined.

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