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A REVIEW OF LIGHT REFLECTION AND TRANSMISSION METHODS IN MONITORING NON-AQUEOUS PHASE LIQUID MIGRATION IN POROUS MEDIA

Motasem Y. D. Alazaiza[1], Su Kong Ngien[1], Wan Mohd Faizal Ishak[2] and Samira A. Kamaruddin[3]
[1]Faculty of Civil Engineering and Earth Resources, Universiti Malaysia Pahang, Lebuhraya Tun Razak, Gambang, Kuantan, Pahang, Malaysia
[2]Centre for Earth Resources Research and Management, Universiti Malaysia Pahang, Malaysia
[3]UTM Razak School of Engineering and Advanced Technology, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia
E-Mail: my.azaiza@gmail.com

ABSTRACT

Recently, image analysis techniques in monitoring non-aqueous phase liquid (NAPL) migration have been gaining attention from researchers. Over the last two decades, photographic methods such as light reflection and light transmission methods have been shown to be applicable and effective tools for characterization and measuring NAPL migration. A review of recent studies published on light reflection and light transmission methods used in NAPL migration is summarized and presented in this paper. Besides discussion on the research efforts, recommendations for future research in using light reflection and light transmission methods are provided. This study concluded that, although having some limitations and drawbacks, photographic methods are still a promising and valuable tool for measuring NAPL migration.

Keywords: NAPL, light reflection, light transmission, image analysis.

INTRODUCTION

Groundwater is the main source of drinking water for many countries around the world. During the past decades, many sources of groundwater contaminants such as leakage of petroleum products, underground storage tanks, pipelines and spills of hydrocarbon have been reported. These affect the quality of groundwater and make it inadequate for human and irrigation uses (Kamaruddin *et al.* 2011a). These contaminants exist in subsurface soil as a separate phase because of their low solubility in water and are known as non-aqueous phase liquids (NAPL), considered as one of the most spread hazardous chemicals (Newell *et al.* 1995). Based on liquid density, NAPLs are classified into two categories; the first category is light non-aqueous phase liquid (LNAPL) which has density less than water and the second category is dense non-aqueous phase liquid (DNAPL) which is denser than water. Relative density influences the migration of NAPL. LNAPL will pass through the unsaturated zone and migrate downward due to gravity then float on the surface of the water table causing deterioration for groundwater quality (Sharma and Mohamed, 2003), while DNAPL will pass through the unsaturated zone and continue its downward migration under the effect of gravity until it reaches the saturated zone. The movements of LNAPL and DNAPL are shown in Figure-1.

It is difficult to observe directly the processes that occur in the porous media of the soil structure. Due to this reason, the investigation of the contaminants in hydrological processes often relies on indirect measurement of the parameters of the system or direct measurements at only a few locations, in some cases as a function of time. Therefore, it is important to find methods or tools that permit direct observation or imaging of the porous media characteristics and the processes that occur within them.

It is not easy to characterize and remediate sites that are polluted with the compounds of NAPL due to their special physical and chemical properties (Mercer and Cohen, 1990). It is difficult to perform field studies on NAPL due to its toxic and hazardous nature, so laboratory and numerical simulations are the natural alternatives. Over the past two decades, more information has been available on laboratory and numerical simulation of NAPL (Kamaruddin *et al.* 2011a).

A review paper was published by (Mercer and Cohen, 1990) about the properties, characteristics and remediation of NAPL. They reported that future research should concentrate on field measurements of NAPL properties to improve knowledge and understanding of the mechanisms of mass transfer. A number of image analysis techniques have been used previously to measure multiphase fluid contents in laboratory experiments (Oostrom *et al.* 2007). These techniques include photon-attenuation methods and photographic methods. Photon-attenuation methods such as Gamma radiation and X-ray are often used in measuring fluid content accurately. These methods have limitations such as slow measurement time, high energy source which is a risk to human health, high cost and cover only small regions at one time. Therefore, because of these limitations, photographic methods such as light reflection method (LRM) (Van Geel and Sykes, 1994), (Conrad *et al.* 2002), and (Ngien *et al.* 2012), and light transmission visualization method (LTV) (Hoa, 1981), (Tidwell and Glass, 1994), (Darnault *et al.* 1998), (Niemet and Selker, 2001) and (Bob *et al.* 2008) are gaining more attention and popularity to measure fluid contents (Bob *et al.* 2008) and (Kamaruddin *et al.* 2011a).

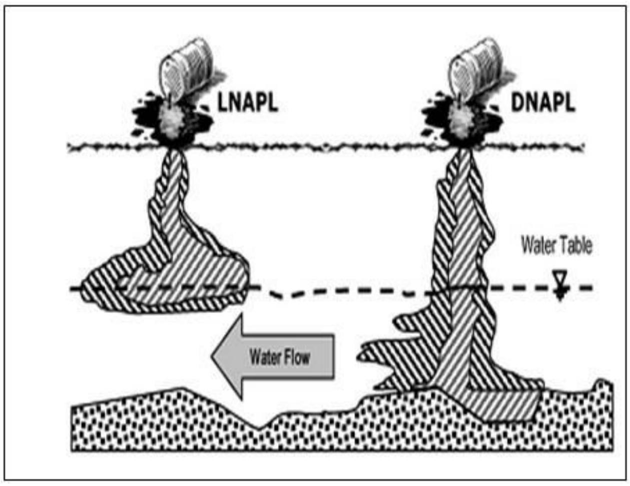

Figure-1. LNAPL and DNAPL movement in subsurface soil (Flores *et al.* 2011).

This paper presents two types of photographic methods that are applied to NAPL migration research. A comprehensive review was carried out to study the performance of light reflection and light transmission methods in monitoring the migration of NAPL in porous media. In addition, the advantages and disadvantages of each method are emphasized which will help researchers to compare and use the best method according to the information available to them. The specific objectives of this work are 1) to familiarize readers with different imaging methods, 2) to identify the advantages and drawbacks for each imaging method, 3) to provide recommendations for future work for researchers.

IMAGE ANLYSIS TECHNIQUES

a) Introduction

The spread of image analysis methods usage in many research fields proves that these methods are very useful especially in studying the behavior of complicated types of contaminants and determination of saturation for different phases in laboratory experiments. Of late, several researchers have conducted laboratory experiments using image analysis techniques. For example, gamma ray radiation (Høst-Madsen and Jensen, 1992), and (Oostrom *et al.* 2003) and X-ray (Tidwell and Glass, 1994) as well as photographic methods including LTV (Darnault *et al.* 1998), (Darnault *et al.* 2001), and (Bob *et al.* 2008), and LRM (Ngien *et al.* 2012) and (Sa'ari *et al.* 2015).Generally, gamma ray or conventional X-ray attenuation techniques do not allow the acquisition of dynamic fluid saturation distribution in the entire flow domain at one time. Because of practical limitations in source intensity, long counting times are needed and only one point can be measured at one time (Darnault *et al.* 1998). These techniques allow measurements with short counting times in the order of seconds but only regions less than 0.5 cm2 can be characterized at a given time (Darnault *et al.* 1998). These limitations lead to more attention on photographic methods which are considered cheaper and easier to use.

b) Photographic Methods

As mentioned previously, photographic methods have been considered as one of the most effective technique in monitoring the migration of NAPLs. All photographic techniques require image acquisition using either a digital camera or video camera depending on the image specification for later processing (Kamaruddin *et al.* 2011b). The main advantage of photographic methods is that images of larger domains can be obtained instantaneously and no radiation is involved. However, the main drawbacks of these methods are that these methods are typically limited to translucent media, require thin flow cells and sometimes require complicated calibration procedures (Oostrom *et al.* 2007). Table-1 shows selected studies that used photographic methods for different measurements such as liquid content, liquid concentration, and other measurements.

LIGHT REFLECTION METHOD

LRM was used in several studies to investigate the infiltration of NAPL under controlled lighting conditions such as using two tungsten light source to light the flume front wall in a dark room (Van Geel and Sykes, 1994) and (Kechavarzi *et al.* 2000). The following sections present the usage of LRM in investigating the migration of NAPL in subsurface system.

a) Measuring Liquid Saturation

The study of (Van Geel and Sykes, 1994) improved the method of (Schincariol *et al.* 1993) in measuring contaminant concentration. They reported that using image analysis in estimating concentration can be an effective tool if more attention is paid to lighting conditions. (Van Geel and Sykes, 1994) quantified the concentraion of N- heptane as LNAPL using LRM. Two tungsten filament flood lights were used in addition to a set of color slides to record the movement of the spills. During the analysis, LNAPL distribution was assumed to be uniform across the depth of the box and the images of the front side actually represented the internal saturations away from the wall. The authors reported that the main disadvantage of LRM is that the change in the LNAPL saturation can only be measured when the water saturation remained constant over time.

Similarly, (O'Carroll *et al.* 2004) used LRM but to estimate the saturation of tetrachloroethylene (PCE) in flow chamber. They correlated the hue from dyed PCE light reflection to known saturations in small glass cells. The authors noted that these observations represent only the PCE occurrence in the first few millimeters of sand adjacent to the glass. Hence, they assumed that the observation of the behavior represented the entire cell thickness. Linear relationship was obtained between the hue and PCE saturation with R2 value of 0.91. The variance in lighting as well as differences in glass thickness between the flow cell and calibration cells led to

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the normalization of the sum of PCE hue to known PCE volume. The estimation method was confirmed using linear trend between the sum of the organic phase hue over all the pixels and the known total volume of PCE with R2 value of 0.94.

Table-1. Using LRM and LTV in measuring of various fluid properties.

Authors	Measurement	Method	Digital camera model	Image analysis software
(Sa'ari et al., 2015)	Migration of dyed toluene	LRM	Nikon D90 DSLR	REIVAL, a MATLAB routine
Ngien et al (2012)	Migration of dyed toluene	LRM	Nikon D40, Suri Technology Sdn. Bhd. , Skudai, Malaysia	REIVAL, a MATLAB routine
(Kamaruddin et al., 2011b)	Infiltration andredistribution of dyedtoluene andbenzene	LRM	-	MATLAB
(Luciano et al., 2010)	Saturation of dyed hydrofluoroether (HFE-7100)	LRM	Digital camera	-
(Simantiraki et al., 2009)	Infiltration and distribution of dyed Soltrol 220 and Diesel	LRM	-	-
(Bob et al, 2008)	Saturation of undyed tetrachloroethylene (PCE)	LTV	CCD camera (Model Number 7486-0002, Princeton Instruments, Trenton, NJ)	Image-Pro Plus software (Media Cybernetics Inc., Silver Spring, MD)
(Konz et al., 2008)	Concentration of salt dye concentration	LRM	Nikon D7	-
(Wang et al, 2008)	Tetrachloroethylene (PCE) mass and mass reduction	LTV	CCD CoolSNAPcf digital camera (Roper Scientific, Inc. Trenton, NJ, USA)	MATLAB
(Flores et al., 2007)	Water and LNAPL saturation	LRM	Consumer grade digital camera Nikon D70s	MATLAB R2006a
(O'Carroll et al., 2004)	Saturation of dyed PCE	LRM	Digital camera	-
(Gerhard and Kueper, 2003)	Saturation of dyed hydrofluoroether HFE 7200	LTV	Three TMC-7DPS color CCD cameras (Pulnix America Inc., Sunnyvale, CA	WIT software (Coreco, St. Laurent, Quebec)
(Weisbrod et al., 2003)	Colloids concentration	LTV	CCD camera (ISI System, Santa Barbara, CA) with a Kodak KAF0400	Transform3.4 (Fortner Software LLC)
(Darnault et al., 2001)	Water content and Soltrol 220 content	LTV	Sony color video camera	IPLab Spectrum V3.00 software from Signal Analytics Corporation
(Niemet and Selker, 2001)	Liquid Saturation	LTV	CCD camera (ISI System, Santa Barbara, CA) with a Kodak KAF0400	Transform3.4 (Fortner Software LLC)
(Conrad et al., 2002)	Saturation of trichloroethylene (TCE)	LTV	CCD camera	-
(Glass et al., 2000)	Saturation of dyed TCE	LTV	CCD camera	-
(Darnault et al., 1998)	Water content and Soltrol 220 content	LTV	Cohu Solid State Color Camera	SP0228 V1.00 Color Tutorial software
(Tidwell and Glass, 1994)	Water saturation	LTV	CCD camera	-
(Van Geel and Sykes, 1994)	Saturation of n-heptane	LRM	-	EASI, P.C.I., Inc. (Toronto, Ontario, Canada- V. 5.0)

(Flores *et al.* 2007) used LRM to measure water and LNAPL saturation distributions. In their study, they took into account the influence of groundwater fluctuations on LNAPL migration in the groundwater. The difference here was dying the water with blue dye and mixing it with sands. The one dimensional column used in the experiment was filled with fully saturated toyoura sand. For different soil samples, there was a logarithmic relationship between saturation and optical density when saturation values as low as 2% were included in the analysis. This relation allowed the authors to measure the distribution of water saturation over time in one-dimensional columnar porous medium in LNAPL-water phase. They reported that the behavior of LNAPLs as expected remain under the groundwater table, as residual LNAPL saturation. Also, the image analysis method used in their study provided good information about the distribution of water saturation over time in an entire column domain for LNAPL-water two phase systems.

(Luciano *et al.* 2010) used LRM to measure DNAPL saturation distribution in a two-dimensional laboratory scale chamber. The authors mentioned that the pixel size is near to the grain dimensions, hence the information returned by the pixel size represented the presence of DNAPL with a grey level value of zero, or its absence with a grey level of 255. Mass balance calculation was used to validate the suitability of LRM. The injected DNAPL amount was compared with the calculated volume from the acquired pictures. DNAPL volume was calculated by multiplying the calculated saturation by the average porosity. The error estimated between the actual injected volume of DNAPL and the estimated volume from image analysis was 6% which affirmed the validity of the technique for measuring saturation.

b) Measuring Liquid Migration and Distribution

(Simantiraki *et al.* 2009) investigated the infiltration and distribution of LNAPL in the subsurface using LRM. Two types of LNAPL (Soltrol 220 and Diesel) were used in two types of different unsaturated sand. Four experiments were conducted using different layers of fine and coarse sands. A calibration curve had to be created for each type of sand and LNAPL, which is considered as the main drawback similar to (Darnault *et al.* 1998) study. From the calibration data, it was concluded that the relationship between intensity and saturation is linear. However, (Darnault *et al.* 1998) proved that hue of the light transmission had a direct relation with water content within the porous media. Comparison between spread velocities was studied and it was noted that the spread of Diesel was faster than Soltrol 220 due to the higher viscosity and density of Diesel. In all the experiments, the flow was slower in the fine sand compared to the coarse sand due to the smaller porosity in the fine sand.

Similarly, (Kamaruddin *et al.* 2011b) used LRM technique in the investigating of the infiltration of LNAPL in vadose zone. Two models A & B were packed with fine sand and silica sand respectively. The LNAPL used were toluene and benzene that were colored with Oil-Red O. From the recorded images, it was noted that clear changes of the shape and intensity of red toluene color in the first day of the experiment were observed, while in the following days no great changes were observed. Also, at the first injection time for toluene, the depth of migration was 8 cm and the spot of toluene was broken into two parts. The range of Hue, saturation, and intensity (HSI) values was from 0.25 to 0.6. After one day of injection, the downward migration of toluene was slower and the depth of migration reached 13.2 cm. The HSI values rose to 0.8. After two days of injection, no significant changes were noted for the toluene. They reported that the migration depths for toluene and benzene were 13.2 cm and 37 cm respectively. It is obvious that the migration depth for benzene was approximately three times the depth for toluene. This big difference may be due to the different soil media used in the experiments.

A significant improvement to the LRM technique was achieved by (Ngien *et al.* 2012) when they used LRM to investigate the migration of LNAPL in one dimensional circular columns packed with double porosity soil kaolin as the soil media, which is considered as clayey soil. The study proved that LRM is viable when using kaolin as a soil medium which refuted the argument of (Oostrom *et al.* 2007) that photographic methods are typically limited to silica sand. Two experiments were conducted using circular columns, and the main difference between the experiments was the size of the soil columns. Two mirrors were used and placed behind the soil column facing the digital camera at 105o to give a complete picture around the circumference of the soil column. The setup of the experiment is shown in Figure-2.

Figure-2. LRM experimental setup (Ngien *et al.* 2012).

Toluene was used as the LNAPL which was colored with Oil-Red O. It was noted that the downward migration was gradually slowing. The explanation could be due to the pressure exerted by the collection of LNAPL above the aggregated sample which had to percolate into the sample surface. The average calculated speed for LNAPL migration for Experiment 1 and Experiment 2 was 0.278 mm/s and 0.417 mm/s respectively. The authors compared these results with the results obtained by (Alias, 2003) who investigated the migration of LNAPL in poorly graded sand. From the results of (Alias, 2003) study, the average speed was 7.5 × 10-2 mm/s, which indicated that this value is much lower than the average speed of LNAPL migration obtained from (Ngien *et al.* 2012) experiments. The study of (Ngien *et al.* 2012) reported that the type of medium is the major difference between their study and (Alias, 2003). The authors conducted another comparison with (Pokrajac and Deletic, 2006) study. The

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average speed of LNAPL was 0.292 mm/s which was around the range of the obtained results from (Ngien *et al.* 2012) study. (Ngien *et al.* 2012) explained that this could be due to the presence of slots along the column wall that resulted in reduction of the air resistance and hence accelerating the migration speed of LNAPL. Thus, LNAPL migration speed in the two studies was approximately the same. From the previous comparisons, it is obvious that the LNAPL migration in double-porosity soil is much faster compared to single-porosity soil due to the presence of secondary porosity features in double-porosity soil.

The most up-to-date study in measurement of NAPL migration using LRM was conducted by (Sa'ari *et al.* 2015). Using the same method, the study of (Sa'ari *et al.* 2015) emphasized the results of (Ngien *et al.* 2012) study that LRM is a valuable tool in monitoring the migration of LNAPL in double-porosity clayey soil media. Two experiments with two different moisture contents were conducted. Water content of 25% and 33% were used with dry kaolin in Experiment 1 and 2, respectively. The same procedures in (Ngien *et al.* 2012) study were followed by the authors. The pouring technique of LNAPL was different between the two experiments. The results showed that the average LNAPL migration speed were 0.04 mm/s and 1.668 mm/s for Experiments 1 and 2, respectively. This is due to higher percentage of water content and uneven compaction for the soil sample in Experiment 2. The authors compared the results of Experiment 1 and 2 with the results obtained by (Ngien, 2012), who used a different moisture content which was 30% in similar laboratory setting. The calculated speed for LNAPL migration was 0.278 mm/s. The behavior of LNAPL migration in 30% moisture content of soil sample in (Ngien *et al.* 2012) study was akin to the behavior in 25% of water content. However, they required different duration for reaching the bottom of the sample. Furthermore, it was observed that the soil sample with 33% moisture content has inter-aggregate pores larger than the soil sample with 25% water content. This observation may influence the speed of LNAPL migration when the soil has more moisture content because the capillary pressure influences the movement of the LNAPL. (Ngien *et al.* 2012) explained that "pores with larger size reduce the capillary pressure that LNAPL has to overcome to enter those pores and thus move through the soil". The limit for water content in double porosity kaolin is 35%.

From the previous studies, it can be concluded that LRM is still a promising and influential technology, particularly in NAPL migration. According to the literature, LRM technique can measure the liquid saturation and content within the whole domain of the sample and do not require much time compared with photon attenuation method. Furthermore, the most significant concern with this method was using it in observing the NAPL migration within double porosity soil clay which is considered the most advanced development for this technique. On the other hand, the drawbacks for this technique are the reflection from light and the need for calibration curves which usually need long time and efforts.

LIGHT TRANSMISSION METHOD

The theory of light transmission technique is the passing of electromagnetic energy into the test media where the distribution of liquid saturation is measured as variation in the light intensity field. There is a linear relationship between saturation and light intensity due to closer matching between refraction index of the matrix and water relative to the matrix and air (Glass *et al.* 1989).

LTV experiments were usually conducted using a thin flow chamber connected with fan for cooling the chamber and a built in lighting source behind the flow chamber. LTV is considered a cheap technique and requires only limited equipment (Wang *et al.* 2008). However, it eliminates the hazards of working with high energy radiation (Niemet and Selker, 2001). Several researchers have attempted to use LTV technique in the last decades due to the previous mentioned advantages. Figure-3 shows a typica experimental setup.

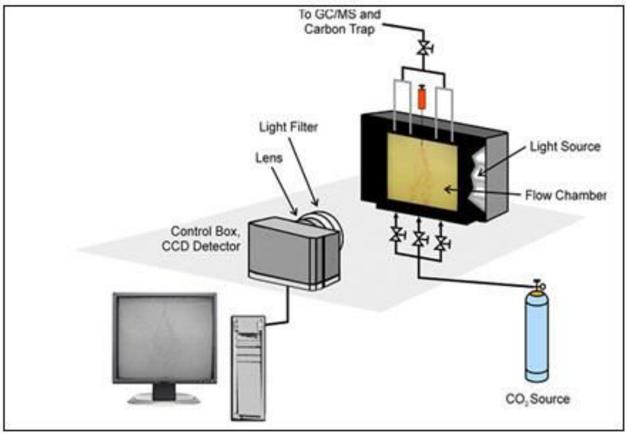

Figure-3. LTV experimental setup.

The following sections present the use of LTV technique in various measurements.

a) Measuring Liquid Content

In general, LTV was first developed by (Hoa, 1981) based on light refraction theory for measuring water content in a sand-filled chamber. Because the relationship between the moisture content and the number of pores filled with water is unknown, an independent calibration curve was needed between saturation and light intensity.

(Glass *et al.* 1989) used LTV method to visualize water content in an entirely 2-D flow chamber. They observed that the relationship between light intensity and water saturation was linear and they argued that this relation is due to the closer matching of the refraction indices of solid and water relative to solid and air.

Thereafter, (Darnault *et al.* 1998) improved the methods of (Glass *et al.* 1989) and (Tidwell and Glass, 1994) to investigate the relationship between hue and water content through full field in a two phase system (water – oil) using HSI format. They found that both saturation and intensity have no considerable correlation to water content. However, a linear relationship was found between hue and water content with an R2 of 0.97. Also, they evaluated the method using mass balance and synchrotron X-ray technique. The error in mass balance was 1%. The main advantage of LTV reported in their study was that the fluid content can be recorded in less than 0.05s throughout the whole flow field. Furthermore, it proved that LTV method is viable in measuring moisture content in 2-D chambers compared with synchrotron X-rays. However, the main drawback reported was developing calibration curves for each type of sand and each camera used.

After few years, (Darnault *et al.* 2001) developed a method to measure fluid content in a three phase system. A two-dimensional calibration chamber was used to obtain a calibration curve between intensity and total liquid content as well as between hue and water content. For correlating hue to water contents, different equations had to be used for correlating above and below the point of 0.076 water content. This point controls the correlation since above this point of water content, hue and water content were uniquely correlated, whilst below this value hue depends on NAPL and air contents in the cell. Furthermore, total liquid content is a function of light intensity and hue. Results obtained from synchrotron X-ray were used to compare with the results from LTV for both static and transient experiments. In the static experiment, R2 for water and NAPL contents obtained from the two methods were 0.97 and 0.92 respectively. For transient experiment, the two methods compared favorably based on measured finger widths in the air-dried and NAPL saturated sand. It was proven that LTV is an effective measurement tool in rapidly changing, three phase systems. The advantages and disadvantages reported by the authors are the same as those in (Darnault *et al.* 1998) study.

b) Measuring Liquid Saturation

(Tidwell and Glass, 1994) study presented a major improvement to (Glass *et al.* 1989) method by deriving equations to relate the saturation to light intensity and light transmission factors at the sand-water and sand-air interfaces. This equation calculates the number of pores filled with water (P) from multiplying water saturation (S) with the total number of pores across the model thickness (K). Moreover, they calculated saturation from measured light intensity by assuming an individual drainage conceptual model and assuming that each pore is either full or empty of water. Their method did not need calibration curve and K can be calculated empirically for each experiment.

Subsequently, (Glass *et al.* 2000) modified the techniques presented by (Tidwell and Glass, 1994) to compute TCE saturation using LTV. TCE saturations can be calculated from energy absorption by the dye, analogous to X-ray transmission equations shown by (Tidwell and Glass, 1994). The comparison conducted by (Oostrom *et al.* 2007) showed that the calibration procedure used by (Glass *et al.* 2000) is easier than the procedures described by (Darnault *et al.* 1998) in two phase systems. The authors noted that the saturation was different from the front to the back of the chamber and the regions with high TCE saturations were close to the regions that were completely water saturated which presented problems in conducting LTV method. They reported that the overall error in TCE volume was around 12% and this error can be reduced using more calibration. However, some errors cannot be avoided and still remained.

The technique described by (Glass *et al.* 2000) was later improved by (Conrad *et al.* 2002) to obtain TCE saturation in a heterogeneous flow cell packed with four types of silica sands. It was noted that the light transmission was influenced by the change in TCE saturation. It was reported that several confounding factors resulted in the failure to apply LTV. First of these factors is the influence of surfactant and permanganate remedial solution on light transmission. Second, the solubilization process of TCE is faster than the dye. Finally, the problems of exposure were taken into account in the finest sand and at the textural interface because of the rather large disparity in light transmission. The previous factors have negative influence on the process of quantifying TCE saturations. The authors stated that the digital pictures can only be used to display qualitative spatial and temporal differences during the course of experiments.

A study by (Niemet and Selker, 2001) was conducted to measure liquid saturation using light transmission. They reported that there was no need for calibration or to measure the empirical parameters in the determination of saturation. Their method was easy to apply since the number of pores (k) can be calculated mathematically pixel by pixel from dry and saturated light intensities. They found that the model with distributed pores size was the best model to measure the liquid saturation from light transmission.

Recently, a major contribution to LTV method was achieved by (Bob *et al.* 2008) who studied the quantification of PCE saturation in a two dimensional, two fluid phase system. For the first time and different from the previous studies, this method was applied to measure undyed PCE saturation in two phase system, water-DNAPL system. Their method did not require calibration curve in case of undyed PCE. However, it was necessary to use a single point calibration step when dyed PCE was used to calculate the change in the transmission factor at the dyed PCE-water interface. Mass balance was conducted. They found a very high correlation with an R2 value of 0.993 between the known amount of PCE and image analysis results obtained from LTV. In case of dyed PCE, stronger correlation (R2 = 0.999) was obtained between the amount of dyed PCE and the results from image analysis. An inverse relationship was found between the volumes of PCE and the errors in mass balance. GS/MS and carbon column extraction were used to compare the mass balance results obtained from LTV.

Similar mass balance results were reported from these independent techniques.

CONCLUSIONS

Many experiments were conducted to observe the migration of NAPL in subsurface system. LRM and LTV methods provide a non- destructive and non-intrusive tool for observing NAPL behavior and characterization in multiphase flow when fast changes that occur in fluid saturation are difficult to observe using conventional methods. It is obvious that there is no perfect method for non-invasive imaging; each method has its advantages and disadvantages. Photographic methods are safe to use and do not have any radiation effect on human health. LRM proved to be applicable in cases of using clay soil as in (Ngien *et al.* 2012) and (Sa'ari *et al.* 2015) studies. However, LRM needs many complicated calibration curves and more steps which means more time and efforts in conducting the experiments. Recently, studies of LTV method showed that calibration curves were not required as in LRM; and the measurement can be rapidly obtained and calculated mathematically using image analysis (Tidwell and Glass, 1994), (Niemet and Selker, 2001), and (Bob *et al.* 2008). The main advantage of the photographic methods is that images of the flow chamber can be obtained instantaneously. Obvious gaps in research include the ability of photographic methods to image the fluid flow in natural porous media. Researches towards using clayey soil in LTV technique are needed. More attention is needed towards using larger depth in flow chambers. Also, studies toward simplifying or eliminating calibration curves from the two methods are needed to develop these methods as fast and reliable estimation techniques.

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