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A mechanism study of airflow rate distribution within the zone of influence during air sparging remediation

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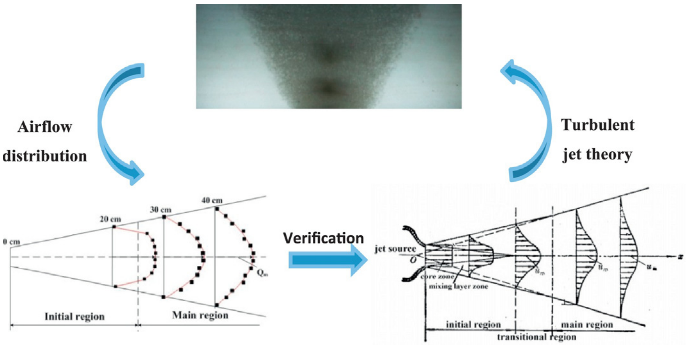
HIGHLIGHTS

- The airflow distribution within the zone of influence was quantitatively analyzed during air sparging.
- The turbulent jet theory was applied to airflow distribution and predictive models of the ZOI for the first time.
- The boundary layer of the ZOI proved to be linear extension through theoretical and experimental study.
- The shape of the ZOI has been demonstrated as a conical zone through our study.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, an improved laboratory two-dimensional airflow visualization device was developed for the quantitative analysis of airflow distribution at different heights from the sparger (20, 30, and 40 cm) within the zone of influence (ZOI). The results indicated that the measured airflow rate distribution appeared Trapezium when the height was 20 cm; however, the airflow rate matched a Gaussian distribution when the heights became 30 cm and 40 cm. The conical shape of the ZOI was observed in the experimental processes. The experimental results verified that the airflow distribution within the ZOI conformed to turbulent jet theory. According to turbulent jet theory, the distribution of the airflow rate changes from Trapezium to Gaussian, and the jet boundary mixed layer is a linear extension in the processes of jets. Through our study, it was found that this theory could be applied to airflow distribution and predictive models for the ZOI in air sparging remediation. The shape of the ZOI should be cone-like and the boundary layer of the ZOI is a linear extension in air sparging process. All the results from this study can provide theoretical support for the design and prediction of air sparging remediation for groundwater pollution.

1. Introduction

With the rapid development of a social economy, organic contamination of soil and groundwater is more and more serious throughout the world. Air sparging (AS) is known as one of the most effective ways for remediating volatile organic compounds (VOCs) in soil and groundwater. The technology has been widely used on account of its high efficiency, quickness and low cost (Adams and Reddy, 2000; Bass et al., 2000; Kim et al., 2014; Song et al., 2015; Tsai, 2007). During air sparging, fresh air is injected into the contaminated aquifer, removing contaminations by volatilization (Rogers and Saykee, 2000; Thomson and Johnson, 2000; Waduge et al., 2004). In this process, the contaminant removal efficiency is controlled by many factors including the air flow pattern, the zone of influence (ZOI), and air distribution during the remediation (And and Zhang, 2001; Hu et al., 2010).

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The air flow pattern in AS process has always been a hot discussion. Ji et al. (1993) observed that air traveled in channelized mode when medium sizes were less than 0.75 mm and bubble mode when particle sizes were greater than 4 mm. Johnson (1998) reported that the air flowed in channel mode when grain sizes were less than 2 mm. Reddy and Adams (2008) observed that a transition from bubble mode to channel mode when the average grain sizes were 2.5 mm (D_{10}) and 0.43 mm (D_{10}); the channel mode occurred in smaller sands with D_{10} less than 0.43 mm. Recently, Song et al. (2015) reported that the air flow patterns transformed from chamber flow to channelized flow when D_{10} was in the range of 0.22–0.42 mm; the channelized flow changed to bubbly flow when D_{10} increased from 1.42 to 2.1 mm. According to the above study, we found that the relationship of air flow patterns and particle size intervals is not uniform specification in AS process, however, the air flow patterns can be divided into two modes according to gas migration processes in porous media: channelized flow and bubbly flow (Ji et al., 1993; Johnson, 1998; Mccray and Falta, 1997; Reddy and Adams, 2008; Song et al., 2015; Thomson and Johnson, 2000; Tsai, 2008). Although the two airflow patterns differ somewhat, they are both gas migration processes in porous media similar to a buoyant jet, which include a momentum balance between the water and airflow (Song et al., 2015).

The extent of the ZOI generated during air sparging has been studied by many researchers in the laboratory and in the field (Hu et al., 2010; Nyer and Suthersan, 1993; Reddy and Adams, 2008; Reddy and Adams, 1998; Rogers and Saykee, 2000; Song et al., 2015). Adams and Reddy reported that the shape of the ZOI was parabolic, whereas several other researchers reported the shape of the ZOI was a cone (Hu et al., 2011; Hu et al., 2010; Ji et al., 1993; Mccray and Falta, 1997; Nyer and Suthersan, 1993; Reddy and Adams, 2008; Reddy and Adams, 1998; Thomson and Johnson, 2000). Ji et al. (1993) reported that the shape of ZOI was parabolic and airflow distribution was sensitive to the heterogeneities of soil matrix through laboratory flow visualization experiments. Mccray and Falta (1997) reported that a numerical simulation of multiphase flow which measured the saturation distribution curve and positive pressure within the ZOI could predict the radius of influence (ROI) of sparging and the shape of ZOI was parabolic. Thomson and Johnson (2000) reported that the processes producing an observed air distribution at a particular site were complicated, and were potentially well suited to modeling with multiphase flow models; however, current models did not provide a tool to predict sparging performance. For the sake of comparing the sizes of the zones of influence observed in different soils, a conical zone of influence may be widely accepted (Reddy and Adams, 2008). Recently, Hu reported that the expansion of the ZOI was attributed to two aspects: the lateral expansion around the air injection point and the enlarged angle of the ZOI (Hu et al., 2011; Hu et al., 2010). Song also agreed with that the view and established a formula for calculating the size of the ZOI radius, and the ZOI radius R could be expressed as follows (Song et al., 2015):

$$R = H\tan\theta + L \tag{1}$$

where H is the sparging depth below the groundwater table, θ is the ZOI angle, which is equal to the arc cotangent of the slope of the linear equation, and L is the lateral expansion length, which is equal to the x-intercept of the linear equation. According to the above experimental research, the existing AS multiphase flow models can describe the airflow field to predict ROI in porous media and the changes of corresponding pressure field. However, it does not reach the airflow channel description of high precision. Hence, there is a big error range by the application of AS model. Laboratory simulation prediction models are also gradually perfect and establish the corresponding formula to calculate ROI. However, there is only empirical formula and there is not the corresponding theory to prop up and explain the experimental results.

The airflow rate is one of the most important factors for contaminant removal efficiency. To date, most researchers agree that the air distribution is uneven: the air flow is greater in the vicinity of the well than at the edges of the ZOI (Adams and Reddy, 2000; Mccray and Falta, 1997; Peterson, 2003; Reddy and Adams, 2008; Thomson and Johnson, 2000). It could be observed that air flow density was greater near the injection well than near the boundaries of the zone of influence (Reddy and Adams, 2008). The velocity of air flow in bubble form can be expressed as follows (Reddy and Adams, 2008)

$$v = \sqrt{\frac{(1.04gr) + 1.07\sigma}{r\rho_w}} \tag{2}$$

where v = air bubble rise velocity, r = bubble radius; σ = air/water surface tension (0.0728 N/m), g = gravitational acceleration (9.81 m/s^2), and ρ_w = density of water (1000 kg/m^3). Roosevelt reported that the velocity of bubbles traveling through media ranged from 16.7 cm/s to 20.2 cm/s and these values were appropriately 20% lower than the reported bubble velocity in water columns (Roosevelt and Corapcioglu, 1998). The velocity at which bubbles travel has been tested in the columns filled with gravel, while the velocity of air within the channels was not known (Ahlfeld et al., 2010; Reddy and Adams, 2008; Roosevelt and Corapcioglu, 1998). Recently, Kim reported that an experimental method has been developed for the quantitative analysis of gas flux, and the distribution of air flux was affected by the depth of the saturated zone. The air flux (J_{am}, cm/min) could be expressed as follows (Kim et al., 2012):

$$J_{am} = \frac{M_s}{A\alpha tC_0} \tag{3}$$

where M_s is the mass of tracer adsorbed in the activated carbon pack, A (cm^2) is the cross-sectional area of the activated carbon pack, α is the convergence factor (dimensionless), t (min) is time, and C_0 (g/cm^3) is the tracer concentration in the air influx to the subsurface. Song reported that the airflow rate distribution within the ZOI was quite uneven and obeyed a Gaussian distribution due to a momentum balance between the water and airflow that was similar to a buoyant jet. The airflow rate could be expressed as follows (Song et al., 2015):

$$Q = f(D) = C + A \times \exp\left(-\frac{(D-x_c)^2}{2w^2}\right) \tag{4}$$

where Q is the airflow rate in units of area within the ZOI (in $cm^3/(cm^2 \cdot s)$), f is the Gaussian function; D is equal to the lateral distance from the sparger (in cm); and C, A, x_c and w are the fitted parameters. To date, the airflow distribution has set up a quantitative analysis and experimental formula; however, there is no clear consensus on the causes of the airflow rate obeying a Gaussian distribution, without the airflow distribution of a quantitative model or theoretical analysis. In other words, there were no corresponding theories to better support these experimental results, such as the boundary layer linear extension, the shape of the ZOI and the airflow distribution.

In summary, there were many researchers in the experimental study of AS. However, both numerical simulation and laboratory simulation remain to be further for the theoretical analysis and research. It is insufficient in the airflow channel description of high precision by AS multiphase flow models and do not find the corresponding theory to prop up and explain the experimental results by laboratory simulation prediction model; Especially that the boundary layer of the ZOI and the airflow distribution within the ZOI in AS process. Hence, it is particularly important to find a reasonable theory to explain the experimental results and establish the corresponding prediction model.

The turbulent jet theory can be described as stating that fluid injects the surrounding fluid with a mixing motion (List, 1982; Rodi and Wolfgang, 1982; Stanišić, 1985). The theory can be divided into momentum jet, buoyant plume and buoyant jet according to the motive force of the jet. The motive force of momentum jet which can be also called pure jet comes from the flow of momentum. The motive force of buoyant