Discontinuous Pore Fluid Distribution under Microgravity—KC-135 Flight Investigations

Lakshmi N. Reddi,* Ming Xiao, and Susan L. Steinberg

ABSTRACT

Designing a reliable plant growth system for crop production in space requires the understanding of pore fluid distribution in porous media under microgravity. The objective of this experimental investigation, which was conducted aboard NASA KC-135 reduced gravity flight, is to study possible particle separation and the distribution of discontinuous wetting fluid in porous media under microgravity. KC-135 aircraft provided gravity conditions of 1, 1.8, and 10^{-2} g. Glass beads of a known size distribution were used as porous media; and Hexadecane, a petroleum compound immiscible with and lighter than water, was used as wetting fluid at residual saturation. Nitrogen freezer was used to solidify the discontinuous Hexadecane ganglia in glass beads to preserve the ganglia size changes during different gravity conditions, so that the blob-size distributions (BSDs) could be measured after flight. It was concluded from this study that microgravity has little effect on the size distribution of pore fluid blobs corresponding to residual saturation of wetting fluids in porous media. The blobs showed no noticeable breakup or coalescence during microgravity. However, based on the increase in bulk volume of samples due to particle separation under microgravity, groups of particles, within which pore fluid blobs were encapsulated, appeared to have rearranged themselves under microgravity.

The study reported in this paper is part of a long-term fundamental research investigation involving design of plant growth systems for crop production under microgravity. Spatial distribution of wetting fluid as well as size distribution of discontinuous pore fluid ganglia under microgravity may strongly impact plant growth conditions, such as water transport and intake by the root in the soil substrate. With gravity, excess water drains along a vertical gradient, and water recovery is easily accomplished; under microgravity, the distribution of water is less predictable and can easily lead to flooding as well as anoxia (Hochn et al., 2000).

Parabolic flight of KC-135 aircraft offers researchers reduced gravity in the order of 10^{-2} g for up to 25 s. The short microgravity period facilitates investigations on the role of gravity in fundamental physical processes. Langbein et al. (1990) conducted pioneering studies on fluid surface and wetting on KC-135 flights by monitoring the variation of contact angle and fluid that wets solid edges. Shah et al. (1993) reported experiments conducted onboard NASA KC-135 flights to detect fluid pathways using embedded electrodes in substrate. They observed that fluid was pushed downward to the bottom of the substrate at enhanced g-level, and during reduced gravity phase the fluid rose and more uniform wetting of the substrate took place. Jones and Or (1999) analyzed flight experiments conducted on Russian space station Mir and a U.S. space shuttle and concluded that water content distributions under microgravity were nonuniform both spatially and temporally. They also noticed the possibility of narrower pore-size distributions under microgravity. Experimental results obtained from the Mir Space Station revealed differences between 1 g and microgravity in terms of capillary flow in granular bed of large particles, most likely due to the gravity effect on water propagation (Yendler et al., 1996). Although prior investigators have paved the way for the research on pore fluid dynamics under microgravity during the past 15 yr, several elements of pore fluid dynamics under microgravity continue to remain as issues of speculation and debate.

The objective of this study is to observe possible particle separation in porous media and the distribution of discontinuous pore fluid ganglia under varying gravity conditions. To achieve this objective, we extended the methods reported in nonaqueous phase liquid (NAPL) literature on observations of pore fluid ganglia in porous media under 1 g condition (Xiao and Reddi, 2004; Reddi et al., 1998; Mayer and Miller, 1992). Mayer and Miller (1992) polymerized styrene monomer, a type of nonaqueous phase liquid, in glass beads, and the solid styrene monomer blobs were sieved to obtain the BSD, which represented the pore fluid distribution. Xiao and Reddi (2004) studied the effect of vibrations on discontinuous pore fluid distribution by measuring the blob sizes of solidified Hexadecane, a petroleum compound immiscible with and lighter than water, entrapped in glass beads in discontinuous ganglia form. These methods were used in the present study to determine the effects of varying gravity conditions provided by KC-135 flight on discontinuous pore fluid ganglia.

MATERIALS AND METHODS

Sample Preparation

In this study, glass beads were used as porous media. Test samples consisted of mixtures of eight different sizes of glass beads (0.8, 1.2, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0 mm) prepared with 4.0 g of each size. Hexadecane, a petroleum compound immiscible with and lighter than water, was used as wetting fluid at residual saturation in glass beads. The higher freezing point of Hexadecane (18°C) allowed the relatively quick onboard solidification of discontinuous pore fluid entrapped in glass beads, so that their size distribution could be measured using wet sieving after the flight. The Hexadecane was dyed red using an organic dye (Oil Red O, Sigma Aldrich, St. Louis, MO).

abbreviations: BSD, blob-size distribution; NAPL, nonaqueous phase liquid.
Residual saturation of Hexadecane was established using the suction system shown in Fig. 1. Aluminum Kodak cases (referred as capsules hereafter) were used as sample containers. The capsule was 3.0 cm in diameter and 4.4 cm in height, and its total volume was 31.1 cm$^3$. The bottom of each capsule was perforated for order for Hexadecane liquid to be drained out. A nylon membrane with 5-μm openings was glued to the bottom of the capsule to prevent air entry when Hexadecane was drained out. The procedure to establish Hexadecane residual saturation in glass beads was as follows.

1) Fill the suction system with de-aired water.
2) Place the capsule tightly on the suction system, and lower the burette until water level reaches the bottom of the capsule.
3) Gently pour well-mixed dry glass beads into the capsule.
4) Gently pour 10.0 mL of Hexadecane into the capsule. The glass beads are now saturated with Hexadecane.
5) Gradually apply suction by lowering burette to drain Hexadecane out of the glass beads, until no more Hexadecane can be drained out. This ensures that Hexadecane has reached residual saturation.
6) Carefully take the capsule off the suction system. Seal the cap to the capsule and store the sample in freezer.

Using this procedure, 16 samples were prepared under identical conditions for the flight experiments. About 0.3 mL of Hexadecane was entrapped in the glass beads, which corresponded to a residual saturation of 4%. The bulk volume of glass beads was 20.0 cm$^3$, and porosity was 0.35. About 11 cm$^3$ of free space above the glass beads in the capsule was left for possible increase in porosity due to particle separation under microgravity.

**Fig. 2.** The trajectory of the KC135 aircraft showing a typical 0-g maneuver. Each parabola consists of a 0-g period of approximately 25 s and 1.8-g period of approximately 40 to 60 s.

**KC-135 Experiments**

The experiments were conducted onboard NASA KC-135 flight in February 2004. Figure 2 depicts a representative flying profile of KC-135 flight. The plane simulated varying gravity conditions by flying in parabolic profile. The flight first created a 1.8-g environment for about 25 s while gaining altitude at an angle of 45°. Then the plane dived downward at a 45° angle to create another 1.8-g condition for about 25 s to finish one parabolic flight (about 15 s). Right: Suction system to establish residual saturation of Hexadecane in capsule. Samples containing the residual Hexadecane ganglia were frozen under 1, 1.8, and 10$^{-2}$ g and then analyzed on ground. To quickly freeze the Hexadecane ganglia within the 25 s of 1.8 g and under microgravity, a nitrogen freezer (MVE Vapor Shipper, Model SC 4/2V, Chart Industries, Inc., Burnsville, MN) was used (Fig. 1). Liquid nitrogen was adsorbed within the wall matrix of the freezer, so that no liquid nitrogen could spill out under microgravity. The nitrogen vapor inside the freezer provided a cryogenic environment of −150°C. Three samples were put into the freezer before the 25 s of microgravity—1 before flight’s takeoff, one during the level segment of the flight (1 g), and one when 1.8 g was reached in the cabin. To prevent samples from floating under microgravity condition, a magnetic strip was glued to the bottom of each capsule, so that the steel bottom inside the freezer can hold the samples down under microgravity. Each capsule was tightly attached to a string, which facilitated careful loading of the samples into the nitrogen freezer under 1 and 1.8 g. Tests were conducted on ground to determine the time required to freeze the Hexadecane fluid. It was concluded that Hexadecane blobs in the glass beads could be frozen within 15 s in the nitrogen freezer.

Due to the high cost of KC-135 flight, only four flights were conducted with one flight per day. Four samples were taken during each flight, and 16 samples were tested in total. The procedure of freezing the samples was as follows.

1) One night before the experiment, four samples, which were prepared under identical conditions and which contained Hexadecane at residual saturation, were taken out of freezer and thawed at room temperature (above 18°C).
2) In the morning, the four samples were stored in an egg tray and taken into KC-135 flight, taking precautions to minimize any transportation disturbance.

3) Before the plane took off, the first sample was loaded into the nitrogen freezer. This sample, labeled as 1-G-1 g, meaning Day 1, on ground under a 1-g condition, was used as a control sample.

4) After the KC-135 plane took off and before the parabola, the second sample was loaded into the freezer during the level segment of the flight. This sample was labeled as 1-A-1 g, meaning Day 1, in the air, under a 1-g condition.

5) When 1.8 g was reached during the parabola, the third sample was loaded into the freezer. This sample was labeled as 1-A-2 g, meaning Day 1, in the air, under a 1.8-g condition.

6) Five to ten seconds after the beginning of microgravity during the parabola, the fourth sample was loaded into the freezer. Five to ten seconds of microgravity allowed possible rearrangement of both glass beads and Hexadecane pore fluid blobs. Then the Hexadecane pore fluid was frozen within the rest 15 to 20 s of microgravity. This sample was labeled as 1-A-0 g, meaning Day 1, in the air, under microgravity condition.

7) After the plane landed, a magnetic bar was used to carefully retrieve the four samples out of the nitrogen freezer; then they were immediately transferred into a cooler in which the temperature was kept lower than 0°C. The same procedure was repeated during the other 3 d of flights to test the reproducibility.

Sample Analyses

The Hexadecane BSDs were measured for the 16 samples that were brought back from the KC-135 flights. The measurements were conducted in a constant temperature room at 6°C. The procedure to obtain the BSD was:

1) The glass beads with entrapped frozen Hexadecane blobs were poured from the capsule into a beaker filled with water colder than 18°C. The glass beads were stirred gently using a magnetic stirrer to detach the Hexadecane blobs from glass beads. Once the blobs were detached, they floated on the water surface and therefore could not be broken up by the stirring.

2) The blobs were wet-sieved using water colder than 18°C.

3) The sieves were air dried in the constant temperature room, and then the blob mass on each sieve was measured.

After the BSDs were derived, statistical analyses using Kolmogorov-Smirnov test (Press et al., 1992, p. 623–625) were conducted to verify whether the BSDs under the gravity conditions were significantly different from each other. The Kolmogorov-Smirnov test (K-S test) can be used to determine whether two datasets differ significantly. The results from each flight experiment form one data set containing four tests—Test 1 is G-1 g test (BSD under 1 g on ground); Test 2 is A-1 g test (under 1 g in the air); Test 3 is A-2 g test (under 1.8 g in the air); Test 4 is A-0 g test (under 0 g in the air). In each of the four data sets, Tests 1 to 4 were compared with each other. The null hypothesis in this analysis is that the two tests being compared are not significantly different from each other. In K-S test, the two cumulative distributions being compared produce a simple measure, $D$, which is the maximum value of the absolute differences between the distributions. If the significance level of $D$ corresponding to the two distributions being compared is greater than a specified level of significance (5%), then the K-S test supports the null hypothesis that the two distributions being compared are not significantly different from each other.

The van Genuchten function (van Genuchten, 1980) was found to be a suitable expression to represent BSDs (Mayer and Miller, 1992; Xiao and Reddi, 2004). Mayer and Miller (1992) proposed to fit BSD using the following van Genuchten expression:

$$F(d) = 1 - \left[ 1 + (\beta d)^{\frac{1}{m}} \right]^{-1}$$

[1]
where \( d \) = blob size (mm); \( F(d) \) is the mass percentage of blobs that are finer that size \( d \); \( \beta \) and \( m \) are fitting parameters: \( \beta \) (mm\(^{-1}\)) increases with the decrease of mean blob sizes; \( m \) is related to the shape of the BSD curve (\( m \) is larger for more uniformly distributed blob sizes).

**RESULTS AND DISCUSSION**

The measured Hexadecane BSDs of the 16 samples are presented in terms of cumulative distributions. Figure 4 shows representative four BSDs from Day 4 experiments, in which the BSDs are the pore fluid distributions under 1 g on ground (labeled as G-1 g), 1 g in the air (labeled as A-1 g), 1.8 g in the air (labeled as A-2 g), and microgravity in the air (labeled as A-0 g). The results indicated that the sizes of pore fluid blobs at residual saturation in the glass beads range from 0.1 to 1.0 mm. The results from Day 1, Day 2, and Day 3 experiments are similar to those from Day 4 test. Therefore, only the results from Day 4 flight were presented in the paper.

The BSDs obtained under the four different conditions for each flight do not show a noticeable difference. Statistical analyses described above were conducted to verify whether the BSDs under the different gravity conditions were significantly different from each other. All of the observed significance levels obtained from the analyses are between 66 and 100%; therefore, all of the data are clearly consistent at the 5% level of significance with the hypotheses that there are no differences among the tests. It is therefore concluded that pore fluid distributions did not change when the gravity condition changed from 1 g on ground to 1 g in the air, from 1 to 1.8 g, and from 1.8 to 10\(^{-2}\) g. Discontinuous pore fluid ganglia showed no noticeable breakup or coalescence during microgravity. This is in agreement with the observations made by Langbein et al. (1990) in similar parabolic flight experiments. In their experiments, solid edges were wetted with water or glycerine; during microgravity, no breakage was observed in 31 parabolae flown with different volumes of water and 24 parabolae flown with different volumes of glycerine.

Although pore fluids at residual saturation did not change significantly under the three gravity conditions, groups of beads encapsulating pore fluid blobs may still rearrange themselves under microgravity. Figure 5 shows the representative frozen samples after the Day 2 and Day 3 flights. With the same initial mass and volume, the glass beads with Hexadecane frozen under microgravity exhibited a higher bulk volume (and porosity). Since KC-135 flight can only provide about 25 s of microgravity, it took about 15 s to freeze Hexadecane pore fluids in glass beads, only 5 to 10 s were left for the glass beads and the pore fluid to freely rearrange themselves. The pictures in Fig. 5 clearly show that glass beads separated and rearranged under microgravity, possibly in groups. The samples frozen during the 25 s of microgravity preserved these changes. This behavior of pore volume increase without separation of pore fluid blobs from glass beads is shown schematically in Fig. 6. This is not inconsistent with the observations made by Jones and Or (1999) who suggested that inter-particle liquid bridges or pendular rings left in the wake of pore drainage provide particle-to-particle bonds that may minimize individual particle movement in microgravity. The observations shown in Fig. 5 clearly indicate the possibility that groups of particles may still move with the encapsulated pore fluid blobs remaining intact.

The 16 BSDs obtained in this study were fitted using van Genuchten function, and the fitting parameters, \( \beta \) and \( m \), are listed in Table 1. When the Day 3 G-1 g sample was excluded due to its nonresidual saturation condition, which occurred due to experimental errors, the values for \( \beta \) and \( m \) fell in relatively narrow ranges, 2.91 to 3.81 for \( \beta \), and 3.33 to 4.65 for \( m \). No particular trend was found for both \( \beta \) and \( m \) when the values under 1.8 and 0 g were compared. This result is consistent with the statistical analysis, which showed that gravity had

![Fig. 4. Cumulative blob size distributions from Day 4 experiments of KC-135 flight.](image-url)
little impact on pore fluid distribution at residual saturation.

**CONCLUSIONS**

Based on the experimental investigations on the effects of gravity on the matrix of porous media and discontinuous pore fluid distribution, the following conclusions were drawn.

1) Microgravity has little effect on the size distribution of pore fluid blobs corresponding to residual saturation of wetting fluids in porous media. The blobs showed no noticeable breakup or coalescence during microgravity.

2) Although microgravity conditions did not result in separating the pore fluid blobs from glass beads, groups of particles (within which pore fluid blobs were encapsulated) appeared to have rearranged themselves under microgravity.

The above conclusions correspond to the behavior of discontinuous pore fluid blobs at residual saturations of the wetting fluid. Future KC-135 microgravity experiments may help to discover the gravity effect on pore fluid distributions at water contents higher than residual saturation. Also, spatial distributions of pore fluid (as opposed to size distributions addressed in this study) within the medium need to be investigated to allow proper design of root modules for microgravity.

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**Table 1. Parameters $\beta$ (mm$^{-1}$) and $m$ in van Genuchten fitting to Hexadecane blob size distributions (BSDs).**

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† $\beta$ increases with the decrease of mean blob sizes; $m$ is related to the shape of BSD curve, $m$ is larger for more uniformly distributed blob sizes.
REFERENCES


