NASA-CR-200865

FINAL
IN-29-CR
OCIT
44108

FINAL REPORT
FOR

JOINT RESEARCH INTERCHANGE
NCC2-5153

CAPILLARY MOVEMENT IN SUBSTRATES IN MICROGRAVITY

Collaborators for Participating Institution

R.J. Bula and N.A. Duffie
Wisconsin Center for Space Automation and Robotics
College of Engineering
University of Wisconsin-Madison

Collaborator for NASA Ames Research Center

Dr. Mark Kliss
Space Technology
Mail Stop 239/23

March 29, 1996

FINAL REPORT
for
JOINT RESEARCH INTERCHANGE
NCC2-5153

CAPILLARY MOVEMENT IN SUBSTRATES IN MICROGRAVITY

R.J. BULA AND N. A. DUFFIE
WISCONSIN CENTER FOR SPACE AUTOMATION AND ROBOTICS
UNIVERSITY OF WISCONSIN-MADISON

INTRODUCTION

A more complete understanding of the dynamics of capillary flow through an unsaturated porous medium would be useful for a number of space and terrestrial applications. Knowledge of capillary migration of liquids in granular beds in microgravity would significantly enhance the development and understanding of how a matrix based nutrient delivery system for the growth of plants would function in a microgravity environment. Thus, such information is of interest from the theoretical as well as practical point of view.

Water and nutrients required for growth and development of plants can be effectively transported within a matrix by capillary force. In order to choose the most appropriate porous matrix (substrate) for a water and nutrient delivery system for growing plants in microgravity, we need to be able to accurately predict fluid transport properties of the substrate in microgravity. This requires an understanding of capillary movement in matrixes and this can most effectively be studied in a microgravity environment. For this reason, a more complete understanding of capillary movement of the fluid within such porous matrix systems is very important to the development of an acceptable water and nutrient delivery system for a space-based plant growth unit.

PRIOR WORK

1. Design of a Modified Unit (CTB-M) for Measurement of Water Front Movement in a Porous Matrix.

A unique device, identified as the Capillary Test Bed- M (CTB-M),was designed, fabricated, and used to study water propagation in substrates during a series of comprehensive experiments carried out on board the Space Shuttle Discovery during the STS-63 mission in February, 1995. A conceptual design of this Capillary Test Bed-M is shown in Fig. 1. The two major components of this unit are a bead column assembly and a reservoir assembly. A valve separates these two components. Approximate dimensions of these CTB-M components are: the reservoir assembly is 215 mm long with an external diameter of 64 mm; the bead column assembly is 215 mm long with an external diameter of 75 mm, and the valve assembly is 15 mm long with an external diameter of 104 mm. The overall length of the CTB-M is 445 mm.

The bead assembly consists of a bead column, two support screens, a hydrophobic membrane, and an external column. The external and bead columns are made from polycarbonate plastic material with transparent walls. The bead column has a grid that can be used to determine the frontal distance of water movement into the matrix material. Support screens (mesh #50) are used to retain the matrix material within the bed. The hydrophobic membrane allows passage of air but retains water inside the CTB-M. The volume available for the matrix material within the bead column is 4.4 cm in diameter and about 16.5 cm in length, which provides a volume of about 251 cm^3.

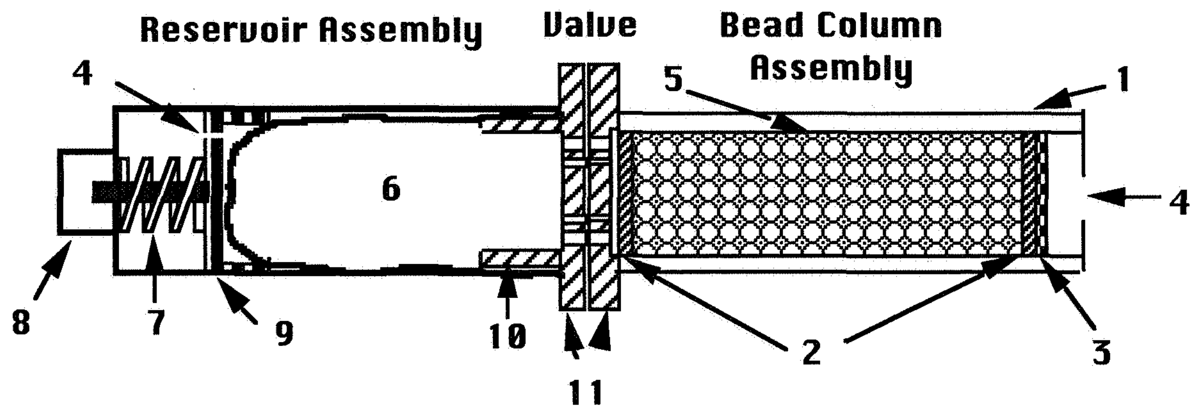

Fig. 1. Conceptual schematics of the modified capillary test bed assembly (CTB-M) used in the experiments conducted during the STS-63 mission.
1- external column, 2- support screens, 3- hydrophobic membrane, 4- vent, 5- bead column, 6- flexible reservoir, 7- spring, 8 - trigger mechanism, 9- compression plunger, 10- valve body, 11- valve disks.

The water reservoir assembly consists of a flexible reservoir, plunger, spring, and trigger mechanism. The reservoir is made from very thin (0.5 mil) polyethylene material. The maximum reservoir capacity is 280 ml. One end of the flexible reservoir is sealed by an O-ring to the valve body.

The valve has holes that are aligned with each other when the valve is in the open position. The valve disk has a cavity next to the support screen with a diameter equal to that of the bead column internal diameter (see Fig. 1). Water from the reservoir flows through the valve holes and fills the valve cavity. This allows water to be introduced into the bead column as a uniform front.

The plunger has a collar (not shown in Fig. 1) that is attached to the plunger to prevent damage (puncture) to the reservoir when the plunger is moved during initiation of the experiment.

To initiate the experiment procedure in any one of the CTB-M units, the plunger **9** is released by the trigger mechanism **8**. The plunger in turn squeezes the flexible reservoir **6**, pushing out a predetermined amount of water. The amount of water is sufficient to fill the cavity in the valve and to wet the first layers of the matrix material. When the valve **11** is opened, water moves from the reservoir through the valve holes, filling up the cavity in the valve, and wetting the frontal layers of the matrix material in the bead column **5**. Following this, capillary force exerted in the granular bed pulls water from the reservoir as the water front moves through the matrix material. The reservoir assembly and the bead column have vents **4** to equalize atmospheric pressure internally and externally of the CTB-M. As water leaves the reservoir, the reservoir collapses in a way so that neither negative nor positive pressure is imposed by the reservoir on the liquid leaving the reservoir. The advancing water front pushes the air out of the matrix material through a hydrophobic membrane located at the end of the bead column. The water front movement is observed through the transparent walls of the bead column and external containment device **(column 1)**.

2. Space Shuttle Experiment (February, 1995)

A series of experiments to determine capillary water propagation in granular matrixes using the CTB-M were conducted during the Space Shuttle Discovery (STS-63) mission as a cooperative research effort involving the Wisconsin Center for Space Automation and Robotics (WCSAR), located at the University of Wisconsin-Madison and Bionetics Corp./NASA Ames Research Center. This experiment was referred to as the Fluid Dynamics in a Porous Matrix (FDPM) experiment. Three test CTB-M units were used during this experiment.

Each of CTB-M units was loaded with glass beads of two different sizes according to the arrangement depicted in Fig. 2. There was no dividing wall separating the areas of particles of different sizes in the bead column. The purpose this arrangement of particle sizes was to study two phenomena during one experiment. Firstly, we wanted to obtain data on water propagation through a granular bed of uniform size particles when the inertia effects are negligible or small. The length of the first section that contained a matrix of glass beads of one size was of sufficient length to provide such data (Yendler and Webbon, 1993). The second phenomena we wanted to study was water movement in a matrix comprised of layers of different size particles (glass beads). A matrix comprised of different size particles would provide data on the rate of water propagation, if any, in each layer of different size particles. This layering arrangement at the end of the bead column would have no effect on speed of water propagation in the section of the column loaded with particles of a single size.

The glass beads (Cataphote, Inc., Jackson, MS) used in the experiments conducted on STS-63 were washed in alcohol, dried, and washed again with distilled water in order to remove all residue from the surface of the particles. One of the CTB-M units, referred to as unit # 1, was loaded with glass spherical beads having a diameter of 1.5 mm and of 1.0 mm. Another CTB-M unit (unit # 2) was loaded with beads having a diameter of 1.0 mm and of 1.5 mm. The third CTB-M unit (unit # 3) was loaded with beads having a diameter of 0.75 mm and of 1.0 mm (see Fig. 2). The bead columns were packed so that the matrix had a porosity of 35 %.

The water reservoir of CTB-M units #1, #2, and #3 we refilled on the ground with 247 ml, 242 ml, and 262 ml of distilled water, respectively. The water was colored with FD & C Red dye No. 40 to enhance tracking of the water front into the bead column. Comparison of the surface tension of water with and without dye conducted in the laboratory showed that the dye had no effect on this physical property of the water.

All three CTB-M units were activated by a crew member according to the procedures described previously in a prior section. Propagation of the water front into the bead column was recorded with a video camera. Activation of each of the CTB-M units was done in two minute intervals starting with unit #3 , then unit # 2, and finally unit # 1. After a predetermined time, the crew member returned to the experimental setup, closed the valves, turned off the video camera, and restowed the CTB-M units.

3. Analysis of Results of the Experiments Conducted During the STS-63 Mission

The results of the experiments conducted during the STS-63 mission are shown in Fig. 3. Water propagated more or less uniformly in CTB-M-B unit # 2 until the water front reached the section of the bead column that was loaded with 1.5 mm diameter particles (see Fig. 2). This happened approximately 67 minutes after initiation of the experiment. The water front then propagated non uniformly, mostly along the layer containing the 1.0 mm diameter beads. Namely, the water front propagation in the layer of 1.0 mm diameter beads along the border of the 1.5 mm diameter beads was slower than the waterfront propagation on the opposite side of this border. The water front reached the 15.5 cm mark in the bead column containing the 1.0

mm diameter beads 83 minutes after the experiment was initiated. At that time, this experiment was terminated. The water front propagated into the portion of the bead column of unit # 2 that contained the 1.5 mm diameter beads to the 12.5 cm mark of the bead column. This amounted to a propagation distance of 1 cm (see Fig. 2).

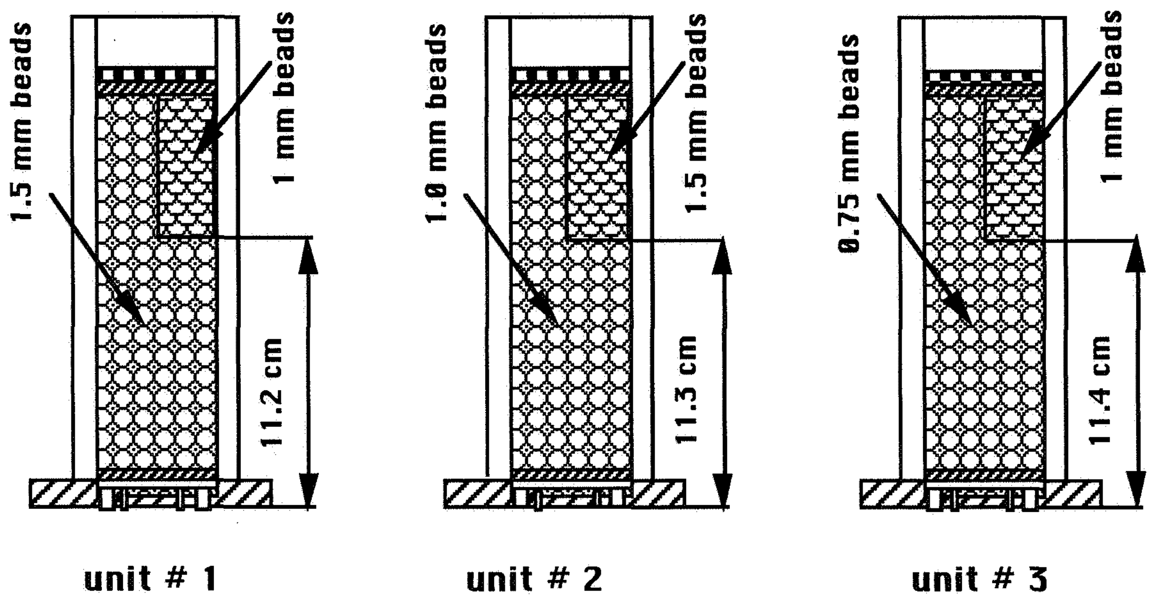

Fig. 2. Diagrammatic representation of the matrix composition of the CTB-M units for the microgravity experiments conducted during the STS-63 mission.

The experiment conducted in CTB-M unit #1, that contained the 1.5 mm diameter beads, indicated that the water front reached the 5.5 cm mark on one side of the bead column and the 7.0 cm mark on the opposite side of the bead column when the experiment was terminated. Therefore, the water front propagation in unit #1 was considered to be uniform. The water front did not reach the layer of 1.0 mm diameter beads situated at the end of the column (see Fig. 2) during the time the experiment was conducted.

In the case of the experiment conducted in CTB-M unit # 3 that contained 0.75 mm diameter beads, the water front was pushed by the plunger to a distance of 4 cm on one side of the bead column. The water front did not move any further into the bead column of this unit.
Post flight analysis of amount of water that penetrated into the bead columns showed that water occupied all the pore space in the bead column. That is, there were no air bubbles entrapped in the wetted part of the bead column as the water front moved into the bead column.

Both experimental goals, namely, to study water front propagation in a granular bed containing all particles of the same diameter and in a layered granular bed of different diameter particles, were achieved in CTB-M unit # 2.

The observation that the water front did not move for any distance into the bed with the 0.75 mm diameter particles was unexpected. Likewise, the propagation of the water front in the CTB-M unit #1, containing the 1.5 mm diameter particles, was not as far as that observed for the CTB-M unit # 2. Previous experiments with the CTB-M units during short duration microgravity exposures (15-20 sec. on parabolic flights of the NASA KC-135 aircraft) have shown that the water front had propagated in the CTB-M units loaded with either 1.5 mm or

0.75 mm diameter particles. One possible explanation for the observed limited waterfront propagation was that the CTB-M units # 1 and # 3 did not function properly when used in the microgravity environment of the STS-63 mission.

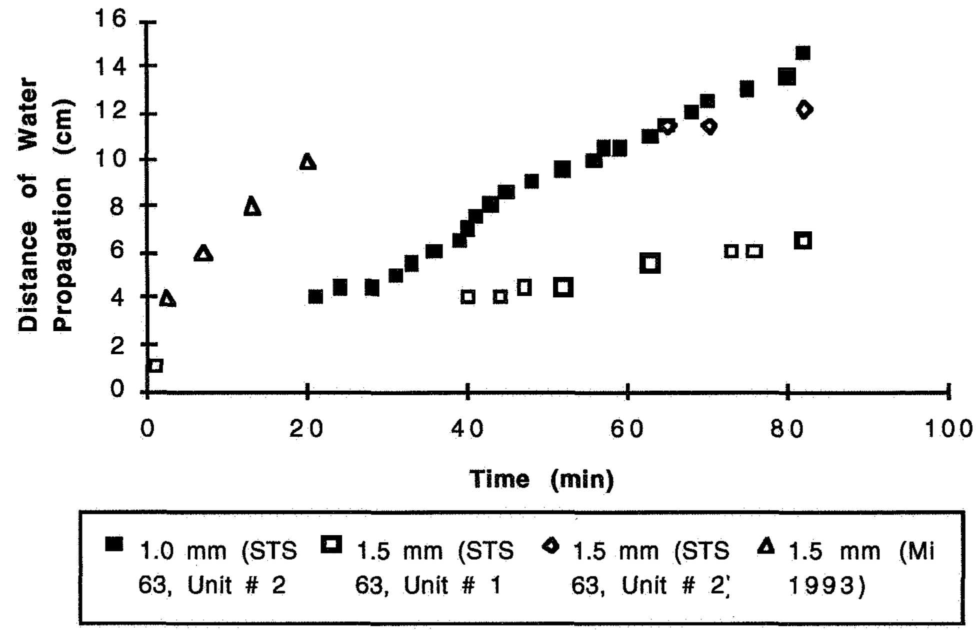

Fig. 3. Comparison of the capillary water propagation in experiments conducted in microgravity during the STS-63 mission and an experiment conducted on the MIR Space Station (Yendler, et al., 1994).

EXPERIMENTS CONDUCTED DURING THE PERIOD OF THE JOINT RESEARCH INTERCHANGE

1. Parabolic Flight Experiments

In an attempt to provide an explanation for the unexpected results obtained with the CTB-M units during the STS-63 experiments, unit # 3 was loaded with the same 0.75 diameter glass particles which had been flown on STS-63 and the following experiment was conducted on a KC-135 flight in November, 1995. The CTB-M was positioned vertically in the KC-135 aircraft with the bead column pointing up. An operator opened the valve at the beginning part of a parabola as the aircraft was entering microgravity, thereby, letting water propagate into the bead column (see Fig. 1). As the aircraft moved through the parabola and as the microgravity period was about to end, the valve was closed. Therefore, water was expected to stay in the bead column during the high gravity part of a parabola. Surprisingly, no water front propagation into the bead column of CTB-M unit # 3 was observed during this KC-135 flight experiment.

2. Ground Experiments

One of the obvious interpretations of the results obtained during the STS-63 and KC-135 experiments is that the magnitude of the capillary force exerted by water in a bed of glass particles of 0.75 and 1.0 mm is much less than would be expected. One of the obvious ways to determine the magnitude of the capillary force was to measure the height of a capillary rise. Calculations based on the formula developed in Yendler and Webbon, 1993, suggests that capillary rise of water in a bed of glass beads having a diameter of 0.75 mm should be approximately 3.4 cm. In an attempt to verify the response indicated from the formula, an experiment was conducted using the apparatus shown diagrammatically in Fig. 4.

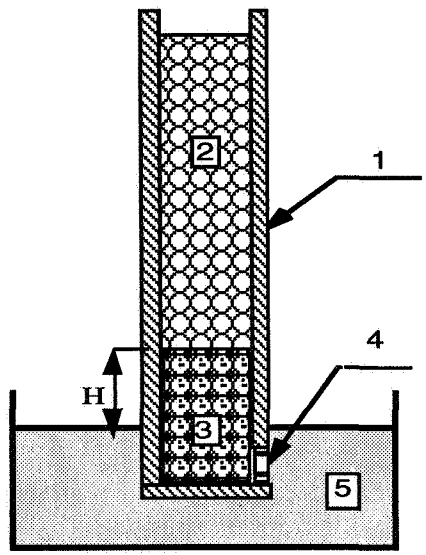

Fig. 4. Conceptual diagram of an apparatus to determine the amount of capillary rise, H, in a bed of glass beads.
1- cell with transparent walls, 2- bed of glass beads, 3- wetted part of glass bead bed, 4- support screen, 5 - water reservoir

The experimental apparatus consists of a cell made from transparent polycarbonate plastic material, support screen, and a reservoir. The cell has a grid to use as an indicator of the distance the water front has propagated into the glass bead bed. The support screen (mesh #50) holds the glass beads within the cell.

After the cell was loaded with dry glass beads, it was submerged into water. The height of the water front, capillary rise, was measured approximately 1 hr after the upward propagation of the front had stopped. Experiments with particles of 0.75 mm used in the STS-63 and KC-135 flight experiments did not exhibit any water propagation or capillary rise. However, a water propagation, or, capillary rise of 1.8 cm was observed when uncleanned particles with a diameter of 0.75 mm taken from the same glass bead supply were used in the experiment. These results indicate that the cleaning procedure, namely, washing the glass beads with alcohol, drying, and washing them again with distilled water, apparently made the surface of the glass beads hydrophobic.

This change in surface properties during the washing procedure did not occur in the case of the 1.0 mm diameter glass beads. Apparently, the change of surface properties of the glass beads to a hydrophobic condition is batch dependent, namely, glass beads from different batches supplied by the same company (Cataphote, Inc., Jackson, MS) may or may not change their surface properties as a result of the described cleaning procedure.

DISCUSSION AND CONCLUSIONS

Ground experimental results reported by Yendler and Webbon, 1993, indicate that the speed of water propagation in a granular bed of glass spherical particles increases with particle diameter up to 1 mm which conforms to existing theories of capillary movement of water in a porous matrix. A decrease of the speed of propagation with particle diameter was observed for particles larger then 1.0 mm. The data shown in Fig. 3 confirm that the speed of water propagation in the granular bed consisting of 1.5 mm diameter particles (CTB-M unit #1) was less then that in the bed consisting of 1.0 mm diameter particles (CTB-M unit # 2). A lack of water propagation in CTB-M unit # 3 that was loaded with 0.75 mm diameter particles, unfortunately did not provide any information as to whether the speed of water propagation in a bed consisting of 0.75 mm diameter particles would be less than that for a bed consisting of 1.0 mm diameter particles.

The data presented in Fig. 3 indicate also that water propagates in adjacent layers of a layered granular bed independently. Empty diamonds in Fig. 3 represent the distance of water propagation through the section of CTB-M unit # 2 which contained 1.5 mm diameter particles (see Fig. 2). The speed of water propagation in a 1 mm diameter particle bed did not appear to change when the water front passed the 11.5 cm distance mark and water began to move through the layered bed. The water movement in the 1.5 mm diameter particle section began with some delay after the moment when water passed the 11.5 cm diameter mark. It is difficult to make a quantitative conclusion, but it is obvious from Fig. 3, that water propagated in the layer loaded with 1.5 mm diameter particles of CTB-M unit # 1 and within the layer of 1.5 mm diameter particles in CTB-M unit # 2 in a similar manner. The fact that the water front propagation was similar in glass bead beds containing the same size particles implies that water propagates in adjacent layers independently in microgravity.

Ground experiments with 0.75 mm diameter particles provided data to explain why the water front failed to propagate in CTB-M unit # 3. These data point out that particles need to be carefully treated so as to avoid affecting the surface property of the glass beads. Any quantitative comparison of experimental data would be valid only if the surface properties of the glass beads used in experiments are similar. Glass beads used in an experiment conducted on the Space Station Mir in 1993 were not treated. Therefore, the differences among the experimental data obtained during the Mir 93 and STS-63 experiments and shown in Fig. 3 may be attributed to the difference in the surface property of the glass beads used in these experiments.

Two steps should be undertaken in order to provide uniformity of surface properties of glass beads or similar particles in future experiments. Firstly, it is necessary to make sure that the glass beads have the same chemical composition. The term "glass" covers a range of chemical compositions and each chemical composition can impart different surface properties to the glass beads. Secondly, special attention needs to be paid to any cleaning procedure that may be used in preparing the beads for the experiment because different cleaning procedures can lead to different surface properties of the glass beads and, consequently, to different results in water front propagation into the glass bead bed. A reference to a cleaning procedure for glass beads can be found elsewhere (Yang, et al., 1988).

Redesign of the CTB-M

The experiments conducted on STS-63 have shown that the CTB-M units used in these experiments could be redesigned to improve their effectiveness in providing more definitive data if some modifications to the reservoir assembly would be made. Our experience has shown that the plunger mechanism can cause some problems that impact the effective functioning of the CTB-M. For example, the moving plunger can potentially rupture the fragile and flexible reservoir. Another problem occurs when a bottom part of the reservoir becomes stuck inside the plunger mechanism. If this happens, the reservoir can not collapse freely during an experiment and this in turn can develop a negative pressure as the water moves out of the reservoir that in turn affects water movement and subsequently the outcome of the experiment. A diagram of a modified CTB-M reservoir assembly that would overcome these operational problems is shown in Fig. 5.

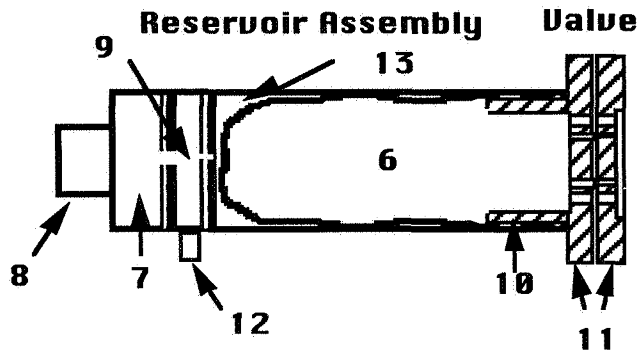

Fig. 5. Conceptual diagram of a modified CTB-M reservoir assembly (only components of the reservoir assembly are shown, see Fig. 1).
6- flexible reservoir, 7- compressed air compartment , 8- 3-way valve turning knob, 9- 3-way valve (exact design TBD), 10- valve body, 11- valve disks, 12- inlet, 13- reservoir compartment.

It is proposed that compressed air be used instead of the plunger mechanism to squeeze the flexible reservoir and to initiate the experiment. The reservoir assembly body would be split into two sealed compartments, 7 (compressed air) and **13** (reservoir), that would be connected by a 3-way valve **9**. The exact design of the 3-way valve needs to be determined. A predetermined amount of air would be pumped into the compressed air compartment through inlet **12** of 3-way valve **9** before initiation of an experiment.

To initiate an experiment, the compressed air from compartment **7** would be released by turning the knob **8**. The compressed air would flow into the reservoir compartment **13** and squeeze the flexible reservoir **6**, pushing out a preselected amount of water. When the valve **11** is open, water moves from the reservoir through the valve holes into the bead column (see Fig. 1). Following this, knob **8** is turned again to open the reservoir compartment **13** to the external atmosphere in order to equalize atmospheric pressure inside the CTB-M unit with that of the ambient environment. The rest of the experimental procedure would follow as described in a previous section.

This design of the reservoir assembly would eliminate the moving plunger and, consequently, the danger of damaging the reservoir by the movement of the plunger. Also, there would be no component inside the reservoir assembly that the flexible reservoir could stick to and therefore not interfere with the collapse of the reservoir as the water is "pulled" from the reservoir by the movement of the water front into the particle bed during an experiment.

REFERENCES

1. Yendler, B., and B. Webbon, Capillary Movement of Liquid in Granular Beds. SAE Tech. Paper No. 932164. 23rd International Conference on Environmental Systems, (1993).

2. Yang, Y.W.; G. Zografi, and E.E. Miller. Capillary Flow Phenomena and Wettability in Porous Media, Part I. Static Characteristics. J. Colloid Interface Sci. 122, pp. 24-34, (1988).

3. Yendler, B.S., B. Webbon, I. Podolski, and R.J. Bula Capillary Movement of Liquid in Granular Beds in Microgravity. SAE Tech. Paper No. 941449. 24th International Conference on Environmental Systems, (1994).