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Experimental study of heat transfer and fluid flow in unsaturated porous media

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EXPERIMENTAL STUDY OF HEAT TRANSFER AND FLUID FLOW IN UNSATURATED POROUS MEDIA

by

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A thesis submitted in partial fulfillment of requirements for the degree of

Master of Science

in

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Abstract

A laboratory experiment was conducted to investigate thermal and fluid flow behavior in an unsaturated porous medium. The experiment consisted of a bed of homogeneous glass beads packed uniformly in a Lexan rectangular box. A cylindrical heat source was located horizontally in the middle region of the bed and the bed was heated to steady state conditions. Water was then introduced uniformly through square nozzles located over the fill material for short periods of time. The box was fitted with a screen at the bottom to keep the porous material intact while allowing the water to flow out. Below the box, an outflow system was located which consisted of a partitioned catch chamber for measuring the special variation of the water flowing out. Measurements in the bed were obtained using two types of devices that are placed in selected locations. These devices include capacitance elements for inferring moisture presence and thermocouples for measuring temperatures.

The experimental results confirmed that the dominant mass and heat transfer mechanisms were vaporization, condensation, conduction, and convection. The simulated medium was observed to develop a dry zone, a two-phase zone, and liquid zone. Moreover placement of a heat source in an unsaturated porous medium causes a shifting of water around the heat source.
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CHAPTER 1

1. 1 Introduction

Heat and mass transfer in porous media are important contributors to processes governing many of the environmental questions. Everything from trying to figure out where groundwater contamination will go to where it came from and how to deal with it depends on these processes. This work deals with issues that have bearing on the prevention of water contamination from nuclear waste that will be buried underground. The effects of water flow and heat transfer around a buried nuclear waste canister are examined in detail.

Combined heat and mass transfer with phase change in an unsaturated porous media has been a topic of much research over the past decade because of its applications in geothermal energy, underground disposal of nuclear and chemical wastes, thermally enhanced oil recovery, water table and groundwater pollutant flow, drying of grains, thermal insulation
performance and solar pond design. An analysis of these processes is complicated by the possible presence of two phases (liquid and vapor) and the varieties of the structure of the porous matrix. Energy transfer in such a medium occurs by conduction, in all of the phases, as well as by convection, evaporation, and condensation. Moisture transport occurs within the voids of the porous medium as a result of vapor pressure gradients, pressure gradients, and thermal gradients. These studies led to a current concept called the "hot repository" design which is a concept for the design of the proposed high level radioactive waste repository. This concept has been analyzed by researchers at Lawrence Berkeley National Laboratory (e.g. [Pruess and Duoghty, 1988]), Lawrence Livermore National Laboratory (e.g. [Buscheck and Nitao, 1993]), and others. In this design, the high level radioactive nuclear waste package is emplaced in the repository such that heat generated by the waste results in temperatures in the surrounding formations that are above the boiling point of water. These high temperatures can persist for thousands of years. As temperatures around the repository increase to the saturation temperature, evaporation of any water flowing vertically toward the repository increases and vapor pressure becomes appreciable. Essentially, the vapor will flow radially away from the heated source. In the cooler region, the water will condense and again flows vertically. In this way water should be diverted around the repository area. The conditions surrounding a heat source are shown schematically in Figure 1. This general phenomena have also been denoted as the "heat-pipe" effect, which implies essentially evaporation/condensation phenomena transporting moisture. Problems of this sort have been analyzed theoretically and analytically through the use of numerical methods.
Figure 1: Diagram of how ground water might be diverted by a "hot repository." In this case the repository heat would cause vaporization of the water, forcing the vapor to flow in an approximately radial direction.
An experiment was conducted to evaluate some aspects of the "heat pipe" effect. The approach was to model the concept in two-dimensions. To apply this, a homogeneous, granular medium in a box was used. For these studies glass beads were chosen to represent the matrix formation, and these were uniformly packed in a rectangular Lexan box. At 10.2 cm (4 in) from the bottom of the box an electrical immersion heater was located horizontally to simulate the heat source. At the top of the Lexan box the inflow system was located where the water was sprayed uniformly through an array of square nozzles. The Lexan box was fitted with screen at the bottom to keep the porous material intact while allowing the water to flow out. Below the Lexan box, the outflow system was located which contained thirteen partitioned catch chambers for measuring water flowing out of the test section. The experimental apparatus is shown schematically in Figure 2.

Measurements were obtained using two types of devices that are placed in carefully selected locations. These devices include capacitance elements for inferring moisture location and chromel alumel thermocouples for measuring temperatures. Locations for placing the various devices in the bed were determined approximately to predict the heat transfer and fluid flow. The field near to the heat source was heavily instrumented with thermocouples but had only a limited number of resistance elements.
Figure 2: A sketch of the experimental apparatus system
The work presented in this thesis investigates experimentally two phase (liquid and vapor) fluid flow and energy transport in an enclosed unsaturated porous medium.

The motivation for this study was to predict the heat transfer and fluid flow mechanisms present within the unsaturated, porous geologic setting like the proposed high-level radioactive nuclear waste repository. The emplacement of heat generating waste in an unsaturated permeable medium is expected to give rise to the development of a heat pipe effect (Pruess et al. 1990). The heat pipe effect can be important in predicting the corrosion of waste canisters and transport of radionuclides through the geologic setting.

The purpose of the experiment described here is designed to provide a model that demonstrates the processes controlling the transport of water and energy in unsaturated porous media. Further it is desired to apply the model to a hypothetical repository in order to predict the basic effects a high level radioactive nuclear waste repository would have on the movement of ground water and energy in unsaturated porous media.
1.2 Problem Description

The thermal behavior of the near field of the emplaced electrical heater was studied experimentally using various measurement techniques. Monitoring the change in the moisture distribution was accomplished using capacitance elements for inferring moisture migration, and these were located at many places throughout the medium. The temperatures were measured at several points of the porous medium using chromel alumel thermocouples. The moisture and temperatures changes gave evidence of the different heat transfer modes in the medium (conduction, convection). However, monitoring the temperatures and the moisture migration helped locate the phase change zones and the drying areas. This facilitated following the formation of a progression of different zones such as the saturated liquid zone, the saturated vapor zone, and the two-phase zone. By careful monitoring these zones, one could identify various phenomena in the phase-change region. This allowed detailed analysis of its effects.
Heat transfer and fluid flow in unsaturated porous media are topics of practical importance and current research interest. Researchers have studied many aspects of these topics using numerical and simulated analyses.

Multiphase flow in porous media with heat transfer involving phase change is one topic that many researchers have studied theoretically and experimentally. Studies of thermal behavior of a multfluid-saturated formation were conducted by Gomaa et al. [1974] showing the effect of vapor saturation and apparent thermal conductivity in a porous medium. A conceptual model was derived that represented both a theoretical derivation and experiment confirmation of the heat pipe concept in porous media. It was found that the dominant mode of heat transfer in porous media saturated with two phase fluid flow under certain temperature conditions.
was a combination of phase change and convection. This has been called the "heat-pipe" effect. The study also shows that the heat pipe effect increases with increasing permeability and porosity of the medium, latent heat of vaporization of the saturating liquid, and vapor pressure.

A heat pipe is an effective tool in transferring heat at high rates by evaporating the liquid at the warm parts and condensing the vapor at the cooler parts of a chamber. The porous heat pipe effects have been investigated extensively by many researchers. However an early investigation was done by Ogniewcz and Tien [1979]. In this study, the governing equations for fluid and heat flow for a one dimensional heat pipe configuration were developed neglecting the effect of fractures but including gravity effects. The governing equations were solved for one dimensional heat pipe configuration. The results show the effects of various fluid and porous medium properties on the heat pipe performance. In a similar study Su and Somerton [1979] proposed a one dimensional theoretical derivation and experimental confirmation for the heat pipe phenomena in porous media. The theoretical derivation described the functional dependence of the heat pipe effect on liquid saturation gradient, capillary pressure, permeability, heat flux and gravity. The results of their study showed that the length of the two phase region is inversely proportional to the heat flux and temperature difference through the system. The presence of the heat pipe effect in a partially saturated porous media can cause large changes in the apparent thermal conductivity.
Several investigators have developed numerical and mathematical models for two phase heat transfer and fluid flow in unsaturated porous media that accounts for processes controlling the transport of water and energy. In particular, attention was focused on the analysis of heat pipe effects in unsaturated or partially saturated porous media that might occur near a high-level radioactive nuclear waste disposal.

The heat pipe behavior in porous media was presented by Doughty and Pruess [1987,1989] in a semi-analytical study. Figure 3 shows the schematic representation of heat transfer regimes and development of the heat pipe region in porous medium due to the emplacement of a high level nuclear waste package. Heat penetrates into the formation as soon as the waste package is buried in the partially saturated permeable medium. This causes temperatures to rise in the surroundings which will vaporize the liquid water present in the formation. The vapor generated in the porous matrix flows radially away from the heat source, then at some time later it condenses on the cooler region of the formation. Under the capillary pressure and gravity, the condensed liquid migrates vertically down the saturated region towards the waste package. As time progresses the saturation gradient causes a backflow of the majority of the condensed liquid vertically toward the heat source. The liquid is then revaporized as it flows toward the waste package and repeats the cycle. The vaporization and condensation cycle is repeated to develop a heat pipe region.

From the Doughty and Pruess study, it was found that, under steady
Figure 3: Schematic of the development of heat pipe in porous medium. [Doughty and Pruess, 1988]
state conditions, three regions with different heat transfer mechanisms exist in the porous medium around the heat source. At the outer boundary a liquid conduction zone dominates where in the inner region there is a conduction dominated single phase vapor zone. The middle domain is a two-phase heat pipe region where heat flow is primarily convective. Also the study shows that the extent of the heat pipe region is influenced strongly by relative permeability and capillary pressure. A porous medium with larger permeability will provide more favorable conditions for heat pipe development.

Extensive theoretical and experimental studies of the homogeneous porous heat pipe have been reported by Udell [1983,1985]. First, he conducted an experimental study on heat transfer in a porous medium heated from above exhibiting the effects of capillary, evaporation, and condensation. From these experiments, it was found that at steady state conditions, three distinct regions existed: a liquid, conduction dominated region at the bottom, a two-phase convection dominated transition zone, and a conduction dominated vapor region at the top. Later he conducted a one-dimensional steady state experimental analysis of the heat and mass transfer in a porous media saturated with the liquid and vapor phases. The result of this analysis shows that convection heat transfer dominates in the two phase zone. In addition, it was found that the driving forces for convection in the heat pipe region are capillary and vapor pressure gradients. The results also predicted the critical dry-out heat flux, the minimum heat flux at which a vapor zone will form for the bottom-heated case. For the horizontally-heated system, it was found that the product of the heat flux and two-phase zone length is
constant for fixed fluid and media properties. Finally, the analysis showed that the effective thermal conductivity of the two-phase zone increased with increasing permeability.

Analytical and semi-analytical solutions in simultaneous flow of fluid and heat associated with high-level radioactive nuclear waste disposal in a porous medium were carried out by Pollock [1986] and Pruess et al. [1985]. Pollock developed a mathematical model analyzing one dimensional vertical transport in an unsaturated porous medium accounting for the coupled transport of heat, two-phase fluid (liquid and vapor), and air. The results he presented illustrated the basic effects of high-level radioactive nuclear waste disposal on the movement of water and heat in an unsaturated porous medium. Emplacement of waste with the high heat generation of spent fuel resulted in a one dimensional temperature rise, vapor pressure, and liquid and vapor fluxes. Thus he anticipated a convective circulation pattern in the vapor phase in two dimensions. Also the analysis showed that the increases in temperature produce evaporation of the water, forcing the vapor to flow away from the heat source. This led to development of an initial dry zone in the vicinity of the repository, and increased liquid saturation away from the heat source due to condensation. The same result was reached by Pruess et al. [1985]. They simulated the simultaneous heat transfer and fluid flow effects on the waste package buried in partially saturated porous formations.

An extensive analysis on the subject of high-level radioactive nuclear waste repository heat driven flow in partially saturated porous media was
performed by Buscheck et al. [1993,1994]. These analyses examined the impact of the repository thermal condition on the hydrological performance of the unsaturated and partially saturated porous formation using "Tough" (transport of unsaturated groundwater and heat) computer codes. In general, these models predict a drying out of the repository formation by boiling of liquid water in the near field of the heat generation fuel and flow of the water vapor to the cooler region. Further, these studies indicate that thermal and fluid flow performance of the unsaturated formation will be dominated by conduction heat transfer. The studies also show that the vapor-phase convection and condensate backflow are influenced sharply by the bulk permeability of the formation. The vapor-phase convection will be increased by increasing bulk permeability. Therefore, the convection heat transfer will be dominated in the vapor zone. Finally, it was found that the region of large contrasting bulk permeability increases the vapor pressure differentials which can drive water vapor into a high permeability region where it condenses and backflows toward the repository.

An experimental study on the heat transfer in a porous media saturated by a liquid was also carried out by Cioulachtjian et al. [1989] using bronze beads to simulate the porous media. Three different configurations were studied: thermal transfer with a flowing liquid, thermal transfer with a flowing liquid with vaporization, and drying of the porous medium initially saturated with liquid. When the heat source delivered sufficient heat flux, the experimental results show the appearance of three zones in the homogeneous porous media. This reaffirmed Udell's experimental finding and Pruess's numerical results mentioned previously. The development of
the two phase zone begins near the heat source and the vapor transport away from the heat source leads to development of a dry out zone.

Finally, an experimental investigation of the behavior of non-isothermal flow in two-dimensional saturated and partially saturated porous media was performed by Ho et al. [1994]. In this paper, physical experiments were conducted using three different saturation levels: fully saturated, half-saturated, and residually saturated porous media to identify non-isothermal flow fields and temperature distributions in a bottom heating and top cooling bed. The experimental results show that vapor convection took place in the unsaturated zone of the half-saturated case. Further, in all three cases two counter-rotating convection cells were observed to develop in the saturated region.

Most of these studies, either numerical analysis or experimental analysis, were done in an initially fully saturated porous medium or a partially saturated porous medium. Heat transfer studies in unsaturated porous media infiltrated by a liquid has had little attention in the literature. For this reason, the objective of the present work will be development of an experimental study of unsaturated porous media infiltrated by a liquid.
CHAPTER 3

EXPERIMENTAL STUDY

3.1 General Outline of Experiment

Coupled thermal and fluid flow processes in an unsaturated porous medium are important in the performance evaluation of some aspect of high level radioactive waste repository. The high temperature fields resulting from the heat production within a radioactive waste repository in a deep underground formation can mobilize the liquid and vapor phases either away from or into the heated region surrounding of the repository. Therefore understanding the behavior of thermally-induced flows is of particular importance because of the possibility of radionuclide release, which could contaminate the mobile ground water if it comes in contact with the radioactive waste.
For this work the medium of interest is granular and initially dry, and the geometry of the whole assembly is such that essentially two dimensional flows of admitted water are able to be examined. A horizontally mounted 1000 W electrical cartridge heater was located 10.2 cm (4 inch) from the bottom of the medium spanning the tank. When the bed was dry, the heater was turned on and came to a steady state temperature typically around 270°C. Water was then introduced from the top of the medium in a spatially uniform manner.

Thermocouples (chromel alumel), located within the packed bed, were monitored as a function of time as the water flows through the system to determine the temperature field. In addition, catch-chambers at the bottom of the apparatus collected the water flowing from the bed. These chambers serve as a monitoring device to see what shifting of the water occurs from the region directly in a vertical line with the heater. This was done to examine the possible shielding effect of the heated area.

3.2. EXPERIMENTAL APPARATUS

A medium-scale experiment was designed to study the heat transfer and moisture migration through the glass beads. In this regard the following work was done:
1. Designed and fabricated the experimental apparatus which includes an inflow system, an outflow system, and a tank to hold the glass beads and water.

2. Drawings of the apparatus setup and individual part components were made using Macintosh CAD drawing software.

A schematic of the experimental apparatus is shown in Figure 2. This consisted of:

a. Plastic box filled with quartz beads: The main part of the experimental setup is 15.24 cm x 43.18 cm x 30.48 cm (6 x 17 x 12 in) in dimensions and considered to be the test section.

b. Inflow system: The top part of the setup constitutes the inflow system which is designed to give a spatially uniform distribution of the water to the quartz beads-filled box.

c. Outflow system: The bottom part of the setup constitutes the outflow system and is used to measure the spatial distribution of the water exiting the test section.
3.2.1 Quartz Beads-Filled Plastic Test Cell:

The middle part of the experimental setup is a box 15.24 cm by 43.18 cm in plan view and 30.48 cm high (6 x 17 x 12 in) and is fabricated from a 1.27 cm (1/2 inch) thick Lexan sheet. Each side of the box was joined together using acrylic solvent cement. The box was then fastened in each side by five 10-32 screws to secure and strengthen it. At 10.18 cm (4 in) from the bottom and 15.24 cm (6 in) from the side a 3.84 cm (1.5 in) hole was drilled, in the front and the back sides of the box, for mounting an electrical heater. A 2.54 cm (1 in) diameter and 15.24 cm (6 in) long 1000 W electrical immersion cartridge heater spanning the box horizontally was mounted in the 3.84 cm (1.5 inch) hole using a 1.27 cm (1/2 in) diameter Teflon plug. Locations were established for mounting thermocouples and the capacitance elements for measuring the temperature and the moisture migration, respectively, inside the box. The box was fitted with a screen arrangement at the bottom to keep the quartz beads from flowing out with the exiting water. The box was uniformly packed with 0.094 cm (0.037 in) diameter quartz beads.

3.2.2 Inflow System:

The inflow system was designed to give a spatially uniform distribution of water to the beads contained in the plastic box. The system consisted of a 5 gallon head tank mounted 2.13 m (7 ft) above the top of the main test cell, 0.19 cm (3/4 in) PVC pipes, control valves, and a set of square
patterned spray nozzles. The square nozzles were mounted on a 12.7 cm by 43.18 cm (5x17 in) plastic plate which was fitted on top of the main test cell. Each nozzle was mounted at 13.34 cm (5 1/4 in) apart, and was attached to a control valve which was placed above the nozzles in-flow line to allow control of the amount of water as well as to balance the flows between the lines leading to the three spray nozzles. The nozzles were connected to the head tank by a 183 cm long PVC pipe as shown in Figure 2.

The system was modified to connect the in-flow line to the city water line in order to control the pressure drop which might affect the uniformity of the flow. The modification was as follows: A 3.05 m (10 ft) hose was connected to the city water line by a control valve. A ball valve and pressure gage were attached to the hose and the in-flow line, then the line was split into two lines by a tee joint. The two lines distributed the flow to the three nozzles as shown in figure 3. Since the flow in the middle nozzle will have twice the flow of the end nozzles, a gate valve was connected to the middle nozzle to control the flow and insure a uniform flow from the three nozzles.

3.2.3 Outflow System:

The out-flow system consisted of a 15.24 cm by 43.18 cm in plan and 15.24 cm high (6 x 17 x 6 in) plastic box fabricated from a 1.27 cm (1/2 in) Acrylic sheet. Twelve grooves were machined in the front and the back sides for placing a partition plate. Then the box sides were joined together using
acrylic solvent cement and fastened by three 10-32 screws. Twelve partition plastic plates spaced approximately 2.54 cm (1 in) apart were placed in the groves and sealed by silicon sealant to create thirteen partitions of dimensions 15.24 cm by 2.54 cm by 15.24 cm (6 x 1 x 6 in). Partitions work as catch chambers. With the partitions to catch the exiting water, it is possible to infer the one-dimensional spatial distribution of water flowing out of the test section. A 15.24 cm by 43.18 cm (6x17 in) Acrylic plate with thirteen drain valves was attached to the bottom of the box.

3.3 Instrumentation

Instrumentation within the medium consisted of two types of devices that are placed in various locations on small positioning wires. The devices include capacitance elements for inferring moisture presence, and thermocouples for measuring bed temperatures.

Eleven small-diameter 30 gauge (0.012") wire chromel-alumel thermocouples are located in specific places around the heater element, as shown in Figure 5.

Capacitance elements are being developed in our laboratory for mapping moisture presence throughout the apparatus [Hansen, 1993]. Since point measurements are desired then capacitance elements are desirable
Figure 4: Sketch of the modified experimental apparatus system.
(not to scale)
devices that will differentiate between porous media conditions that are unsaturated and saturated with liquid water. The idea for this sensor is to detect the presence of water through a change in capacitance of the experiment media. The elements are made from simple duplex solid conductor wire, small diameter 24 gauge (0.056 in), with tips on one end stripped of insulation and the two wires epoxied on each side of a small dielectric spacer as shown in Figure 6. The conductor for this wire was a copper conductor. The gap between the probe was reduced to less than .094 cm (.037 in) which is the size of the glass beads. A probe gap smaller than the beads should minimize any interference from the porous medium itself. Six of these capacitance element probes were built. The distribution of these devices is shown in Figure 7.

3.4 Assembly of the Experimental Apparatus

A platform to support the apparatus 53.34 cm (21 in) off the floor was fabricated from wood. On top of the platform thirteen holes were drilled to port the outflow system drainage lines. The outflow system box was then placed on the platform with the screen frame mounted on top. Next the test cell box was placed and sealed on the screen frame by silicon. The thermocouple probes and capacitance elements were positioned on small wire on a U-shaped screen and placed inside the test cell box. An electrical cartridge heater was then mounted in the box. With all instrumentation installed, the bed was packed with 0.094 cm (0.037 in) quartz beads. The packing method consisted of shaking and tapping the box while filling to
insure consistent bed porosity. Finally the square nozzles were mounted on a
12.70 cm by 43.2 cm (5 x 17 in) plastic plate which was fitted on top of the
main test cell. The nozzles were then attached to the head tank by a set of
control valves, ball valve, and 1.91 cm (3/4 in) PVC pipe. The test section
was insulated completely by 7.62 cm (3 in) thick polyurethane foam.

The system was connected to a Labview data acquisition program. This
program includes libraries of functions and development tools designed
specifically for data acquisition and instrument control. More details of this
program are given in Appendix II. This system also allows the ability to view
the data while it is being collected, as well as to save it for further processing.
Figure 5: Location of thermocouple placements in the center plane of the bed via a front view of the apparatus.
Figure 6. Design of the capacitance elements used for determining moisture content.
Figure 7: Location of capacitance element placements in the center plane of the bed via a front view of the apparatus.
4.1 Preliminary Procedure

The different instruments used in the experiment were adjusted and calibrated before the actual experimental run. First, the inflow system was adjusted and calibrated to insure a uniform flow in each nozzle. The procedure involved an iterative process of adjusting the control valve until a desirable flow was reached in each nozzle. Next the capacitance elements within glass beads were calibrated in both dry and fully saturated conditions with liquid water. The results of these calibrations are shown in the
appendices. However, in order to calibrate these elements a circuit was built to convert a capacitance reading into a voltage reading which was easier to use with the data acquisition program. Finally, the relative permeability of the beads, which is a constant of proportionality relating to the ease with which a fluid passes through a porous medium, was measured experimentally. This was done using the falling head method (a detailed description is given in Appendix III) by passing water through the medium and measuring the associated head drop. The permeability was determined to be $1.35 \times 10^{-11}$ m$^2$ with 40% porosity.

Prior to packing the beads, the thermocouples and capacitance elements which were to be located within the bed were fixed in position and their locations recorded. The thermocouples and the sensors were placed in approximately 5.08 cm (2 in) increments from the heater.

The complete experiment was run for several times without the heater on in order to see the distribution of the water exiting the test section. The water collected in each partition was measured and recorded. The test cell was unloaded and the wet quartz beads were dried. Then the bed was packed with dry beads using the same packing method as before to insure consistent bed loading. The system was then ready for operation.
4.2 Operational Procedure

Once the test cell was loaded, the apparatus was ready for the next test. The heater power was adjusted at the desired level to give the desired test temperature. The thermocouples and capacitance elements were connected to the Labview data acquisition program and turned on. The program recorded the temperatures and moisture sensor outputs at regular time periods up to steady state. The system required 4-7 hours to reach steady state conditions. Once steady state is established, the Labview program is changed to record data every five seconds. Five minutes later, the water is introduced in a spatially-uniform, time varying manner from a head tank above the experiment into the dry bed. Then the system is allowed to run to steady state which took from 1-3 hours. After steady state is reached, the power was turned off, the Labview program was stopped, and the data saved. The water collected in the partitions of the outflow system was measured and recorded. It is worth noting that the experimental data was collected using the apparatus in Figure 2 and the modified apparatus shown in Figure 4. The apparatus shown in Figure 2 was used to collect the temperature field information while the apparatus in Figure 4 was used to determine the moisture content data. This way the results of the moisture content can be used to confirm the temperature field results.
CHAPTER 5

EXPERIMENTAL RESULTS AND ANALYSIS

5.1 Temperature Profiles

The purpose of this experiment was to determine temperature profiles and moisture migration as a function of time. Figures 8 through 10 show the experimental results for temperature profiles obtained from the steady state condition. A transient condition occurred for a certain period of time after the water was admitted into the test section.

The temperature of the 1000 W cylindrical cartridge heater was set to approximately 273 °C, which is the maximum formation temperature currently expected from nuclear waste storage. The temperatures within the
bed exhibited the expected trends of linear temperature profiles in the steady state condition. However, the heater power was controlled at 490 W to give the steady state temperature, which was recorded by thermocouple 7, of 274.0 °C, and 1.5 gal of water was admitted into the bed during a 35 second time period.

Figure 8 gives an example of the temperature field obtained in the vertical median plane of the heater with thermocouples located as shown in Figure 5. From the temperature profiles obtained it appears that the heat transfer is dominated by conduction in the porous medium. Temperatures in location 8 show a very small change which is an indication of that area being a vapor region. At steady-state conditions the temperature in location 9, which is 10.16 cm (4 in) above the heater, is below the boiling point. As the water reaches this location the temperature takes a sharp drop and stays below the boiling point. This indicates the effects of being saturated with liquid water. Therefore the effects of boiling, vapor, and condensate flow are apparent in a line vertically through the heater area. Vapor is driven away from the heater region (locations 6 and 8) to where cooler temperatures (location 9) cause it to condense. This sets up a saturation profile. There is essentially no temperature variation in location 6 indicating there is no fluid reaching this location.

The temperatures on the horizontal line from the heater are shown in Figure 9. Thermocouple 7 was at the top surface of the heater, and thermocouples 4 and 10 were 5.08 cm (2 in) away from the heater axis at each
side as shown in Figure 5. Thermocouples 10 and 11 were 10.16 cm (4 in) away from the heater. Thermocouples 7 and 10 show the steady state dry temperatures with apparently no water reaching this location. Accordingly, a dry-out region was developed closer to the heater due to the thermal shield created by the high temperature field (274 °C). As the water flows toward the heat source, boiling occurred, creating a vapor zone. Consequently, the temperature at location 4 takes a slight dip but stayed above the boiling point of water, which is an indication of presence of superheated vapor. However, the straight line portions of the temperature profiles in Figure 9 imply that conduction is the dominant heat transfer mechanism in these regions. Temperatures in locations 1 and 11 show a similar behavior where the temperature takes a small increase sensing vapor before water reaches that location. The high porosity of the medium allows the water vapor to travel faster to this point than the liquid water. These temperatures simply flatten as sufficient time elapsed which is attributed to the condensate of the vapor convecting heat away from the boiling zone.

Figure 10 shows the temperature profiles in the plane away from the heater. As the water reaches positions 3 and 5 these temperatures take a sharp drop, and after a short time the temperature profiles flatten out. This represents the effects of these thermocouples being bathed in the high heat capacity fluid. The temperatures at these positions indicated that the phase change has occurred in this region. This region, which can be identified as a mixing zone, is located between the vapor zone (location 4) and the liquid zone (locations 1 and 2). Here water is evaporated at the intersection with the vapor zone and the vapor is condensed within the mixing zone. The return
flow of condensate back toward the boiling region establishes a heat transfer mechanism called the "heat pipe" effect. In the heat pipe region, the heat transfer mechanism is driven by the convection of latent heat. Therefore, the flattening of the temperature profile in Figure 10 is primarily attributed to the heat pipe effect. Thermocouple 2 is located in the liquid zone because the temperature there takes a small drop which indicates the effects of being saturated with liquid water. Since thermocouple 2 is located in a cooler region of the bed water vapor condenses and deposits its latent heat of vaporization there. This is indicated by the jump in the temperature profile at that point.

Figure 11 schematically summarizes the results recorded in the water's infiltration period during the experimental run. These conditions were clearly visualized by looking through the transparent front wall of the test cell. Visual information was attained by distinguishing between the liquid regions (darker contrast) and the dryer regions (lighter contrast). This visual information was supported by the experimental results which show that the heater is surrounded by a dry zone in which heat transfer was undoubtedly dominated by conduction. Accordingly, high rate heating was capable of driving steam away from the heat source faster than the rate which liquid can flow toward the heat source, thereby causing a dry-out zone to form. At some distance away, a two-phase zone, the heat-pipe region, may be present, where the vapor and liquid are mixed. In the heat-pipe region heat flow is primarily convective. Beyond the two-phase zone a liquid region is present which is dominated by conductive heat transfer, where temperatures are too low for evaporation or for the heat-pipe effect to occur.
The results of this study were in good agreement with the numerical and semi-analytical results presented by Pruess et al.[1988]. In their study a model of mass and energy transport was used to develop semi-analytical solutions for temperature, saturation fields, and pressure around the heat source. The study results show three domains may exist around a cylindrical heat source emplaced in a partially saturated formation: a conduction dominated inner vapor zone, a two-phase zone, and a liquid outer conduction zone. Also comparisons with the previously reported experimental studies of Udell et al. [1985] and Cioulachtjian et al. [1989] indicate an agreement between their results and experimental results reported here. Accordingly, these results confirm Udell's, Pruess's, and Cioulachtjian's findings that under steady-state conditions, three distinct regions may appear around the heat source in porous media.

Finally, the distribution of water collected in partitions on the bottom of the experiment's test cell is shown in Figure 12. The result in Figure 12 shows the ratio (heated case over unheated case) of the amount of water collected in each partition at the end of experimental run. Several characteristics are to be noted. It is apparent there is some water deficiency under the heater location which is attributed to divergence of the water around the heater. Water is decreased by 70-77% in partitions 6, 7, and 8 and 56% in partition 9. In contrast, partitions 2, 3, 4, 5, and 11 show an increase of 47-53%. Another item of significance is that the water collection is not symmetrical which is attributed to channeling that occurs due to packing the
Steady-state heater temperature = 294.0 °C
Water admitted into the bed = 1.5 gal
Time required for water to exit the bed = 59 sec

Figure 8: Temperature profile vs time for thermocouples 6, 8, and 9.
Steady-state heater temperature = 294.0 °C
Water admitted into the bed = 1.5 gal
Time required for water to exit the bed = 59 sec

Figure 9: Temperature profile vs time for thermocouples 1, 4, 7, 10, and 11.
Steady-state heater temperature = 294.0 °C
Water admitted into the bed = 1.5 gal
Time required for water to exit the bed = 59 sec

Figure 10: Temperature profile vs time for thermocouples 2, 3, and 5.
Heater temperature = 294.0°C
Water admitted into the bed = 1.5 gallon
Time required for water to exit the bed = 59 seconds

Figure 11: Schematic of conditions achieved at water admission and exit time during the experimental run as inferred from data. (A front view of the test cell is shown but not to scale)
Figure 12: The distribution of water collected in the partitions on the bottom of the experiment's tank.
bed with instrumentation present. A final item of note is that differences between cases are always seen. This is due to the repacking of the bed that must occur each time. Note that repacking of the bed must occur both in the heated and unheated cases if water is admitted.

5.2 Moisture Migration Profiles

Moisture migration in the bed was monitored using capacitance element sensors as a function of time. The results are depicted in Figure 13 through 14. Each figure consists of three plots that show the moisture profile in vertical and horizontal locations in the bed. The results shown here are for the system when it reaches steady state conditions and the water was sprayed on the bed. It is important to notice that the moisture content in these figures represents the ratio of mass of water to mass of dry beads where zero is a dry condition and 0.174 is a fully saturated condition.

Figure 13 shows sample results for the sensors located in the vertical median plane of the heater. These sensors were placed in approximately 5.08 cm (2 in) increments from the heater axis as shown in Figure 7. The sensor in location 1 shows a moisture content change from dry to fully saturated conditions when the water is admitted to the bed. As time progress, the moisture profile takes small drop which is an indication of the water drain out of the test cell. The saturation level stays high in this location which confirms the temperature profile result mentioned above as being in a liquid
region. When the sensor in location 2 indicates the liquid front has arrived, it takes a slight jump but stays in the low saturation region. This might be attributed to be in the vapor region as shown in Figure 11. Finally the location 3 moisture profile is shown to be in a dryer region which is a good indication of being in a dry-out zone as is confirmed by the temperature results.

The profiles of moisture content indications in a horizontal line are shown in Figure 14. The sensor in location 4 shows a quicker jump and a settling in the intermediate saturation region. The moisture profile in location 4, which is located in the vapor zone, shows a series of cycling patterns. Such a cycling pattern is attributed to cyclic evaporation phases where the vapor flows away from the heat source and the condensate returns back toward the heat source. Location 5 shows a small moisture change profile. This represents the possibility that the location is in a dry-out zone. Finally location 6 shows the expected trend of a sharp increase to fully saturated conditions since it is in a region far away from the heater. As time progresses the moisture profile takes a small dip which is due to drainage of water into the partitions of the outflow system.

By examination of the behavior of sensors 2, 3, 4, and 5 an important observation can be made. It can be seen that the distribution of moisture was not radially symmetric relative to the heater axis. This might be attributed to uneven packing of the bed with instrumentation.
Steady-state heater temperature = 294.0 °C
Water admitted into the bed = 1.5 gal
Time required for water to exit the bed = 59 sec

Figure 13: Moisture migration in the bed for sensor 1, 2, and 3.
Steady-state heater temperature = 294.0 °C
Water admitted into the bed = 1.5 gal
Time required for water to exit the bed = 59 sec

Figure 14: Moisture migration in the bed for sensor 4, 5, and 6.
CHAPTER 6

SUMMARY AND CONCLUSION

This study examined the impact of thermal conditions on fluid flow in an unsaturated porous medium. Most of the attention in this work was focused on the temperature field and moisture content profiles in the near field of a horizontal cartridge heater. This illustrated the basic effects of the heat source on the movement of water and energy in unsaturated porous media. In general, the fluid flow is influenced the temperature field through the formation of a heat pipe and creation of a boiling zone. The heat convective effects in the heat pipe region have a local, transient effect on the temperature distribution and moisture change. However, the increase in temperature induces evaporation and vapor transport away from the heat source region which results in the development of a dry zone surrounding the heat source and increased liquid saturation levels away from the heater, due to condensation.
The study shows that the porosity is an important component for heat and fluid flow that developed during the test. The pores of the porous medium served as flow paths for steam, served as condensation points where cool temperatures exist, and served as drainage flow paths for condensate forming in the cooler zones.

The following remarks will serve as summary and conclusion.

1) The results presented in this study demonstrate some possible effects of water interaction with a horizontal heat source which may have implications for high level radioactive waste disposal.

2) The experimental results show that 75% of the water is diverted around the heater area.

3) Under steady state conditions, the results show the appearance of several zones in the homogeneous porous medium:
   a. dry and vapor zones where conduction heat transfer is dominant.
   b. convection dominated two-phase heat pipe zone.
   c. far field liquid saturation region.
The results of this study resemble a degree of agreement with the experimental results of Udell and Cioulachtjian et al., and the numerical results of Pruess et al. presented in the literature survey.

Future work can be done to improve the experiment in several areas. First, from the prior work in this general area, it is apparent that the permeability (and thus the porosity) of the medium play an important role in the outcome of the results. Therefore, experimental work needs to be done using a range of porous media with different permeabilities (and porosities). Also the experiment can be run with a range of temperatures instead of one temperature to determine the effect of this important variable. Finally, improvement of the inflow system should be done to insure consistent uniformity of the input spray.
CHAPTER 7

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APPENDIX I

Capacitance Element Calibrations

The moisture sensors used in this experiment are a solid state capacitive type which were built in our laboratory. These sensors work with sensing the changes of moisture by conductance, resulting in linear capacitance changes as a function of moisture content.

Capacitance element sensors can easily be interfaced to a data acquisition system by converting the capacitance reading into a voltage output. Figure 15 shows the schematic diagram of the capacitance to voltage converter circuit. The circuit features the use of an operational cmos amplifier (ICL 7556) and precision instrumentation capacitors and resistors. The circuit requires a 2.5 V DC input. This design will maintain excellent DC accuracy down to micro-volts. The circuit output was connected to the Labview data acquisition system for automatic monitoring.
Figure 15: Schematic diagram of capacitance-to-voltage converter circuit for the use with the capacitance element sensors.
The capacitance element sensors were calibrated using the capacitance-to-voltage converter circuit. Since the purpose of using these sensors was the monitoring of the moisture migration through the porous medium bed, the sensors were calibrated in dry and fully water saturated fill material. The calibration procedure was as following:

1. The sensors were connected the converter circuits, and the circuits were connected to the Labview data acquisition program. Then the system was turned on.

2. 579.6 grams of dry glass beads were measured and placed in a 400 ml graduated cylinder. This represented a zero moisture content (dry) condition.

3. The sensors were inserted into the dry glass beads and monitored until a constant reading was achieved.

4. The Labview program was stopped and the data collected was saved.

5. 100 grams of water was added to the dry glass beads. This represented a 100% moisture content (fully saturated) condition.

6. The sensors were inserted into the fully saturated glass beads and monitored until a constant reading was achieved, then the data collected was saved.

7. The data collected were plotted and curve fitted.
Figures 16a through 16f show the results of the sensor calibrations. The ratio of the moisture content (mass of water over mass of glass beads) in these figures was plotted versus the voltage reading and curve fitted using a first order polynomial equation. The resulting equation was used in the data collected from the experimental run to generate the moisture content plot.
Figure 16a: Calibration of capacitance element [sensor 1].

Figure 16b: Calibration of capacitance element [sensor 2].
Figure 16c : Calibration of capacitance element [sensor 3].

\[ y = -2.1217 \times 10^{-2} + 8.1604 \times 10^{-2}x \]

Figure 16d : Calibration of capacitance element [sensor 4].

\[ y = -3.2891 \times 10^{-2} + 8.5432 \times 10^{-2}x \]
Figure 16e: Calibration of capacitance element [sensor 5].

Figure 16f: Calibration of capacitance element [sensor 6].
LabView Data Acquisition

LabView is a program development applications package which uses a graphical programming language to create programs in block-diagram form instead of text-based languages (that create lines of code). In addition LabView is a general purpose programming system that includes libraries of functions and development tools designed specifically for data acquisition and instrument control. LabView programs are called "virtual instruments" because their appearance and operation imitate actual instruments. A virtual instrument is a software construction that has the characteristics of an actual instrument. The program has two main functions that are combined together for the program to work. These functions are an interactive user interface which is called a front panel and receiver instructions known as a block diagram. The front panel is a program representing an assembly of electronic components that perform the virtual instrument functions, and a
calling interface for communication with other virtual instruments. The block diagram is the virtual instrument source code which contains input/output, computational, and sub-virtual instrument components interconnected by wires directing the flow of data.

Thermocouple and voltage virtual instrument programs are developed to collect data from the experimental apparatus. These programs acquire data from an SCXI-1100 (Signal Conditioning eXtension for Instrumentation), linearize it, and save it into a file. SCXI-1100 is a high performance, signal conditioning and data acquisition system that can accommodate 32 differential channels. SCXI-1100 is a module for signal conditioning of thermocouples, volt, and millivolt sources. Figures 17 and 18 show schematic diagrams for the thermocouple program and voltage program, respectively.
Figure 17a: Schematic front panel for thermocouple virtual instrument program.
Figure 17b: Schematic block diagram for thermocouple virtual instrument program.
Figure 18a: Front panel for voltage virtual instrument program
Figure 18b: Schematic block diagram for voltage virtual instrument program
APPENDIX III

Coefficient of Permeability via the Falling-Head Method

Permeability generally relates to the propensity of a porous medium to allow water to move through its void spaces. According to Darcy's law, the flow rate of water $q$ through a porous media of cross-sectional area $A$ is directly proportional to the imposed gradient (slope) $i$, or $q = kiA$. The constant $k$ is known as the coefficient of permeability which indicates the ease with which a fluid passes through a porous medium. The falling head method is one of the general laboratory methods that is available for determining the coefficient of permeability of a porous media directly. The coefficient of permeability is necessary to determine the time for fluid to travel between two points. This method is accurate to within about one order of magnitude.
A falling-head permeability test was run using the standard compaction mold permeameter. This permeameter contains a standpipe, top cap with rubber gasket and inlet orifice, test mold, porous stone at the base, and outlet drain hose. A drawing of the apparatus is shown in Figure 19. The first step of the general test procedure was to saturate the glass beads with water. Water was then allowed to move through the specimen under a falling-head condition, while the time required for a certain quantity of water to pass through the specimen was measured and recorded. Using these data one can determine the coefficient of permeability. The actual step-by-step procedure was as follows:

1. The permeameter mold with the base plate and gasket attached was weighed. The inside diameter of the permeameter mold and its length were measured and recorded.

2. A dry sample of glass beads was placed into the permeameter mold and compacted to a desirable density. The permeameter mold with base plate and gasket attached plus compacted beads was weighed and the density of the sample was determined.

3. With the outlet tube open, the sample was saturated with water. The specimen was assumed to be saturated when water in the inlet tube on top of the mold reached equilibrium with water exiting the mold.
Figure 19a: Sketch details of the falling-head test apparatus.
Figure 19b: Sketch details of the test mold.
4. After the specimen was saturated the outlet tube was clamped. The standpipe was then filled to a convenient height, and the hydraulic head across the sample was measured.

5. The test was started by opening the outlet tube and simultaneously the test was timed. The water was allowed to flow through the sample until the standpipe was almost empty. The outlet tube was clamped and the elapse time was recorded. The hydraulic head was measured.

6. The standpipe was refilled to the same height as in step 4 and step 5 and was repeated five times.

The coefficient of permeability was calculated using the formula [Liu and Evett, 1990]

\[ k_T = \frac{al}{At} \ln \frac{h_1}{h_2} \]

where \( k_T \) = coefficient of permeability, m/s

\( a = \text{cross-sectional area of standpipe, m}^2 \)

\( l = \text{length of specimen, m} \)

\( A = \text{cross-sectional area of glass beads specimen, m}^2 \)
\[ h_1 = \text{hydraulic head at beginning of test, m} \]
\[ h_2 = \text{hydraulic head at end of test, m} \]
\[ t = \text{total time for water in standpipe to drop from } h_1 \text{ to } h_2, s \]

The computed coefficient of permeability was the value for water at 24 °C at the time when the test was conducted. It was necessary to correct this permeability to that for 20 °C by multiplying the computed value by the ratio of the viscosity (\( \alpha \)) of water at 24 °C to viscosity of water at 20 °C. The ratio of the viscosity (\( \alpha \)) of 24 °C water to that of 20 °C water was 0.9095 [Liu and Evett, 1990].

**Falling Head Data Sheet**

Sample Dimensions: \( D = 3.30 \text{ cm} \)

Area = 8.55 \( \text{cm}^2 \)

Mass beads + pan init. = 941.9 g

Ht = 7.10 cm

Mass beads + pan final = 1037.6 g

Vol = 60.73 \( \text{cm}^3 \)

Mass of the sample = 95.7 g

Density = 1.576 g/cm\(^3\)

Area standpipe = 0.40 \( \text{cm}^2 \)

Temperature = 24 °C
Test data

<table>
<thead>
<tr>
<th>Test no.</th>
<th>$h_1, \text{cm}$</th>
<th>$h_2, \text{cm}$</th>
<th>$t, \text{s}$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>39.5</td>
<td>16.7</td>
<td>28.23</td>
</tr>
<tr>
<td>2</td>
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<td>17.0</td>
<td>28.02</td>
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<td>3</td>
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<td>16.8</td>
<td>28.16</td>
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<td>5</td>
<td>39.5</td>
<td>17.1</td>
<td>30.75</td>
</tr>
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</table>

\[
k_T = \frac{a}{A} \frac{h_1}{\ln \frac{h_1}{h_2}}
\]

\[
k_T = \frac{0.4 \times 7.1}{8.55 \times 28.3} \ln \frac{39.5}{16.7} = 0.00989 \text{ cm/sec}
\]

\[
k_{20} = \alpha k_T = 0.9095 \times 0.00989 = 9.0 \times 10^{-5} \text{ m/sec}
\]

The following equation was used to determine the permeability:

\[
K = \frac{k_{20} \mu}{\rho_{\text{H}_2\text{O}} g}
\]
where \( K \) = permeability, \( m^2 \)

\( k = \) coefficient of permeability at 20 °C, \( m/s \)

\( \mu = \) viscosity of the water, \( N s/m^2 \)

\( \rho = \) density of the water, \( Kg/m^3 \)

\( g = \) acceleration of gravity, \( m/s^2 \)

Then the permeability is

\[
K = \frac{9.0 \times 10^{-5} \times 1468 \times 10^{-6}}{1000 \times 9.80} = 1.35 \times 10^{-11} m^2
\]