Experimental study of drying of a porous medium at sub-residual saturations

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EXPERIMENTAL STUDY OF DRYING
OF A POROUS MEDIUM AT SUB-RESIDUAL SATURATIONS

by

A. Kumar Sathappan

Bachelor of Mechanical Engineering
Bharati dassan University
1990

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree
Department of Mechanical Engineering
Howard Hughes College of Engineering

Graduate College
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Entitled

Experimental Study of Drying of a Porous Medium at Sub-Residual Satuations.

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

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ABSTRACT

Experimental Study of Drying of a Porous Medium at Sub-residual Saturations

by

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Dr. Robert F. Boehm, Examination Committee Chair
Professor of Mechanical Engineering
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An experimental study has been conducted to understand the drying effects in sub-residual saturated systems. Different flow rates and isothermal wall temperatures were used in the experiments. In two experimental runs, the test section was maintained at room temperature and gas flow initiated. Four other cases were started initially with heating up the porous medium with no flow, and then letting nitrogen gas flow through the test-section after a steady-state temperature distribution had been reached (denoted in what follows as the "steady heating case").

Temperatures throughout the bed and entering and exiting humidity values as a function of time among other data were collected for analysis. These were then used for the mass balance calculations, which were compared to values taken from a digital balance. These showed localized evaporation and dryout phases. Generally the lower temperature cases showed good comparison between the humidity-based calculations and the digital balance readings. At higher temperatures an initial large drop in mass was
indicated which was not shown from the humidity-based calculations. Possible sources of discrepancies are discussed.
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CHAPTER 1

INTRODUCTION

OVERVIEW

Drying of porous materials is usually encountered in many engineering applications including nuclear waste disposal, geothermal systems, building thermal insulation, enhanced oil recovery, drying of grains, solid-matrix heat exchangers and packed bed chemical reactors. Moisture transport and drying phenomena in porous media can have important implications, in particular, in the design of the underground repository. Therefore, the study of this type of problem becomes very important and for decades has attracted the attention of several authors.

Porous materials attract and hold water molecules in quantities that are directly proportional to the ambient relative humidity. At lower relative humidities a thin film of liquid is deposited on the internal surface of the material, compared to at higher relative humidities some of the pores can be entirely filled with liquid. The moisture, in fluid form (both liquid and vapor), migrates through the porous material as a result of capillary action and pressure, gravity, molecular diffusion, and thermal gradients. This concept has been analyzed by researchers at Lawrence Berkeley National Laboratory [Pruess and Doughty, 1988], Lawrence Livermore National laboratory [Buscheck and Nitao, 1993],
Université de Sherbrooke, Canada [Kallel and Galanis, 1993], Institut National des Sciences Appliquées, France [Perrin and Javelis, 1993] and others.

Experiments were conducted to determine humidity in flows exiting the porous medium, as well as temperatures within the medium during drying, for the isothermal boundary condition. In order to do this, an aluminum test-section containing glass beads was used. Two humidity sensors and various thermocouples were used in the data acquisition process. Water was used as the displaced fluid and nitrogen gas as the displacing fluid.

Different wall temperatures and gas flow rates were chosen for each individual experiment and some interesting phenomena were observed, which are then compared. Previous experimental work in this area was done by Jennifer Vallebuona, which involved a constant wall heat flux boundary condition and at different gas flow rates.

The two-fold motivation for this study evolved from the facts that (i) higher flows of fluids at reduced capillary pressure and elevated temperatures could cause more moisture to penetrate into the repository, thereby aiding corrosion of the canisters and (ii) the numerical study conducted by Lingineni et al. [1995] show that humidity values can be underpredicted in sub-residual saturations when the capillary pressures are arbitrarily fixed to a maximum value.

1.2 PROBLEM DESCRIPTION

The drying phenomena in the unsaturated porous media were studied experimentally using various measurement techniques. The temperatures were measured at several points in the porous medium using chromel alumel thermocouples. Humidity
capacitance sensors were used to acquire humidity values and these were located at both the inlet and outlet of the test-section. A digital balance was used to read the weight at specific time intervals. Monitoring the temperature and humidity changes as well as the digital balance readings 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.
Drying of porous media and related topics are of much practical importance and current research interest. Researchers have studied many aspects of these topics using analytical, experimental and numerical analyses.

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 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 Pollack [1986] and Pruess et al. [1985]. Pollack developed a mathematical model analyzing one dimensional vertical transport in an unsaturated porous medium accounting for the coupled transport of heat, two-phase filled (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. In addition, the analysis showed that the increases in temperature produced 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].

A concept called "hot repository" had been analyzed in detail by Izzeldin et al. [1994]. Experiments they conducted show that a repository can generate a large amount of heat where boiling of water might occur giving rise to vaporization in the radial direction. In the far-field, condensation might occur allowing the liquid moisture to flow downwards. A heat-pipe effect was in place, which diverted moisture away from the repository.
An experimental study on the heat transfer in a porous medium 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 the 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' 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.

An extensive analysis on the subject of high-level radioactive nuclear waste repository heat driven heat 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 drying 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. Finally, it was found that 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.
CHAPTER 3

APPARATUS AND EXPERIMENTAL PROCEDURE

3.1. INTRODUCTION

Our objective was to experimentally determine the drying phenomena of the porous medium, which in this case is quartz beads, for different flow rates and constant wall temperatures. A scaled down experimental model was used in the laboratory, as shown in Fig. 1. The aluminum test-section measured 16 inches in length and an outside diameter of 1.5 inches as shown in Fig. 2. The inside surface of the model was thoroughly cleaned to create a smooth surface. The quartz beads were sorted out from a lot quantity, using a sieve-shaker, to the required dimensions and were thoroughly cleaned as well. Compressed nitrogen gas, regulated with a valve, provided the forced convection needed for the experimental runs.

The test section was wrapped with heating element and had to be insulated with fiberglass wool to prevent loss of heat from the walls to the atmosphere. This method of insulation helped minimize heat lost to the environment and allowed us to calculate the effects of radiation and conduction through the walls of the test section.

Thermocouples placed at various locations monitored the wall and inside temperatures in the test section along with the incoming and outgoing gases and the ambient. Humidity sensors measured the inlet and outlet humidities of the test section.
Figure 1. Diagram of piping and instrumentation used in the drying experiments.
All the data were collected through the data acquisition device LabVIEW and were later analyzed.

3.2 EXPERIMENTAL APPARATUS

The test section is constructed of a 16" long aluminum cylinder that has an inside diameter of 1.5" and two plexiglass windows (0.275" x 5.625"). Aluminum material was chosen for this application because it is rust-resistant and has a high thermal conductivity. Quartz beads with an average diameter of 0.037" are used as the porous medium in the test-section. A metal screen is placed at the bottom of the test-section to hold the porous medium in place, and to let water and nitrogen pass through.

Ten 30 gauge K-type thermocouples have been used in the test-section to measure the temperatures with a maximum of 0.75% error. These are placed at several locations within the test section as shown in Figure 2. Four other thermocouples were used in recording wall temperatures and the ambient temperature data.

Industrial grade nitrogen gas has been used as the displacing fluid, whereas water is the displaced fluid. Nitrogen gas was chosen because of its similarity with the composition (79% by weight) of the natural environment. The mass flow rate of nitrogen gas is controlled by a servo valve / feedback control system. The mass flow rate data are recorded using the digital signal conditioning and data acquisition devices. The flow controller has a ±1% accuracy, based on the full range of 1 SLPM.

Two relative humidity sensors are used to measure the moisture content of the inflowing and outflowing gas. The voltages of the humidity sensors are recorded as a function of time. Calibration of the humidity sensors is done with reference to the water
Figure 2. Schematic diagram of the test section used in the drying experiments.
content and temperature following the ASTM Designation E 104 – 85, which is shown in Appendix I.

3.3. PROCEDURE

3.3.1 EXPERIMENTAL OPERATION

First, the test section was filled with distilled water and was allowed to drain until it had no water flow out. For the 60°C and 90°C cases, heating was initiated using a solid state temperature controller. Time was allowed until steady state temperatures were reached, as shown on the temperature profiles, before the gas flow was initiated.

Thermocouples collected temperature data from various locations in the test-section along with ambient and inlet and outlet sections. Humidity sensors located at the inlet and outlet sections measured relative humidities. When steady state had been reached, nitrogen gas flow was turned on via a flow regulator controlled by a servo-valve mechanism. Flow rates of 0.5 l/min and 1.0 l/min were used in our experimental runs. Other instrumentation used includes a small-range (0.5” water maximum and +/- 1% accuracy) differential pressure transmitter for measuring the pressure drop across the porous medium. The output voltages from the transmitter have been recorded. Weight readings of the entire test section with respect to time have also been recorded during the test, and these were accomplished with a digital balance.

Atmospheric pressure was noted for each separate run. The humidity values, pressure difference and flow rate were noted in the form of voltage readings, then were translated later into their own units. Two computers with LabVIEW data acquisition system (one for temperature measurement and the other for voltage measurements such
as pressure, relative humidity, etc.) were used. The data were recorded every 10 seconds.

Heating on the wall is accomplished with an Omega 1” x 8’ heating tape (maximum output rating of 8.6 W/in²).

Data were collected until after the dry-out phase occurred. This was noted from the temperature readings, which increased gradually back to the set point of the heater when the sub-residual water at that location was removed by the nitrogen gas.

3.3.2. DATA ANALYSIS

Relative humidity measurements in capacitance are converted to a percentage value. They are then used to calculate the humidity ratio. This in turn, was used with the gas flow rate to estimate the water vapor loss rate from the test section. The way this was done is shown below.

Humidity Ratio,

\[ \omega = \frac{\text{mass of water vapor}}{\text{mass of dry nitrogen}} \]

Using the ideal gas law,

\[ \omega = \frac{P_{\text{H}_2\text{O}(g)}}{P_{\text{N}_2}} \left( \frac{R_{\text{N}_2}}{R_{\text{H}_2\text{O}(g)}} \right) \]

\[ \omega = \frac{P_{\text{H}_2\text{O}(g)}}{P_{\text{N}_2}} \left( \frac{M_{\text{H}_2\text{O}(g)}}{M_{\text{N}_2}} \right) \]

\[ \omega = 0.6433 \frac{P_{\text{H}_2\text{O}(g)}}{P - P_{\text{H}_2\text{O}(g)}} \]

Relative humidity,
\[ \phi = \frac{P_{H_2O(g)}}{P_{H_2O(sat)}} \]

\[ m_{N_2(g)&H_2O(g)} = \rho \cdot Q \]

where, \( Q \) = volumetric flow rate, \( m^3 / hr \)
\( \rho \) = average density, \( kg / m^3 \)

For certain experimental running time, \( H \) (in hours):

Mass of water vapor in / out,

\[ m_{H_2O(g)} = \omega \left( \frac{kg \ of \ water \ vapor}{kg \ of \ dry \ nitrogen} \right) \times H(\text{hrs}) \times m_{N_2(g)&H_2O(g)} \left( \frac{kg \ of \ dry \ nitrogen}{hr} \right) \]

Mass Balance Equation:

\[ m_{in} - m_{out} = \frac{dm}{dt} \]

This mass difference is compared with the digital weight scale reading, thereby a percentage error could be calculated.

Analysis of flow rate:

Superficial velocity,

\[ V_s = -\frac{\Delta P \times K}{\mu \times \Delta X} \]

where, \( \Delta P \) = pressure differential, inches of \( H_2O \)
\( K \) = intrinsic permeability, \( m^2 \)
\( \mu \) = dynamic viscosity in N.sec/m²

\( Q = V_s \cdot A \)
where, \( A \) = cross-sectional area of the test-section.
CHAPTER 4

RESULTS AND DISCUSSION

4.1 TEMPERATURE PROFILES

In the room temperature cases, the temperature profiles tend to have a predictable pattern. The temperature drops and climbs for the bottom part of the test-section are gradual and happen over a long period compared to the top portion of the test-section. This could be caused by the gravity effects and the nitrogen flow in that direction. Temperature values shown by TC2 and TC9 (see locations in Fig. 2) indicate readings by thermocouples that are within the test-section, but are not in contact with the glass beads.

Bigger temperature drops for 1.0 l/min flow rate cases (Figs. 4 a-b) compared to the 0.5 l/min cases (Figs. 3 a-b) are noted along with a quicker dryout period. This could be understood from the postulation that surface tension decreases with increasing flow rates. It took about 1460 minutes to dry the bed for the 0.5 l/min case (Fig. 3b) versus only 700 minutes for the 1.0 l/min case (Fig. 4b) as seen by the outlet temperature readings.

Regarding the 60°C experimental runs, similar trends are noted. Temperature drops are noticeably larger for the 1.0 l/min case (see Fig. 6b) compared to the 0.5 l/min case (Fig. 5b). Nitrogen flow was turned on roughly about the same time in both cases.
Temperature Profile (1 l/min, room)

Figure 4a
Humidity Profile (1 l/min, room)

Relative Humidity (%) vs. Time (min)

RH in (%) vs. RH out (%)
Weight Reduction (1 l/min, room)

Time (min)

Weight (g)

Figure 4d
Temperature Chart (0.5 l/min, 60 deg C)

Temperature Chart (0.5 l/min, 60 deg C)

Figure 5a
Temperature Chart (0.5 l/min, 60 deg C)

Figure 5b
Temperature Chart (0.5 l/min, 60 deg C)

- T, inlet
- T, outlet
- T, wall top
- T, wall middle
- T, wall bottom
- T, ambient

Figure 5c
Humidity Profile (0.5 l/min, 60 deg)

![Graph showing humidity profile with time in seconds and relative humidity (%) on the y-axis. The graph indicates a decrease in humidity following gas flow initiation.]

Figure 5d
Weight Reduction (0.5 l/min, 60 deg)

Gas Flow Initiated

Figure 5e
Temperature Chart (1 l/min, 60 deg C)

Figure 6a
Temperature Chart (1 l/min, 60 deg C)

Figure 6b
Temperature Chart (1 l/min, 60 deg C)

Figure 6c
Humidity Chart (1 l/min, 60 deg C)

- Rhin (%)
- Rhout (%)

Gas Flow Turned On

Figure 6d
Weight Reduction (1 l/min, 60 deg)

Figure 6e
Temperature Profile (0.5 l/min, 90 deg)

Gas Flow Turned On

Figure 7a
Temperature Profile (0.5 l/min, 90 deg)

Figure 7c

Gas Flow Turned On

- T, inlet
- T, outlet
- T, wall top
- T, wall middle
- T, wall bottom
- T, ambient
Humidity Profile (0.5 l/min, 90 deg)

Gas Flow Turned On

Figure 7d
Figure 7e

Weight Reduction (0.5 l/min, 90 deg C)

Time (sec)

Weight (g)

Gas Flow Turned On

from balance (g)
mv reduce (g)
Temperature Profile (1 l/min, 90 deg)

Gas Flow Turned On

Figure 8a
Temperature Profile (1 l/min, 90 deg)

Figure 8c

Gas Flow Turned On
Figure 8e

Weight Reduction (1 l/min, 90 deg)

Time (sec)

Weight, g

Flow Turned On

mv reduce (g)

from balance (g)
and it took a total of about 12600 seconds for T8 readings to climb back up versus 8100 seconds in the other case.

The 90°C cases are different from the room temperature and 60°C cases. The temperature drops shown by the thermocouple T7 in figures 7b and 8b are significantly greater compared to the other cases. In the 1 l/min case, T7 value drops close to 47°C from the steady-state temperature. This shows a predominantly capillary transport mode in the high moisture content region.

4.2. HUMIDITY PROFILES

The room temperature cases (Figs. 3c and 4c) have longer periods of high outlet relative humidities compared to the higher temperature cases (Figs. 5d, 6d, 7d and 8d), because $P_{\text{sat.}}$ is higher for the latter cases. Here, the drying process is primarily due to the gas flowing through the porous medium, temperature having a minimal effect.

The 60°C and 90°C cases (Figs. 5d, 6d, 7d, and 8d) show a relatively quick drop of the outlet humidity values, even though longer periods of low outlet relative humidities exist. This could be drawn from the temperature profiles, which show the drying front advancing from the top to the bottom of the test-section.

In all the cases, the saturation always increased with distance from the drying front, as can be noticed from the temperature charts. The measured temperature profiles are consistent with the relative humidity measurements, the temperature is highest at the drying surface throughout the drying process.

4.3. WEIGHT REDUCTION

Decrease in mass of the experimental apparatus with respect to time is an important parameter in the study, as shown in Figs. 3d, 4d, 5e, 6e, 7e and 8e.

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Measurements from the digital balance are compared to results from the integration of the mass lost in the flow. The latter is inferred from the mass flow rate of the gas and the relative humidity measurements. In the room temperature cases (Figs. 3d and 4d), calculated water loss tends to be similar to digital balance readings. In the 60°C cases (Figs. 5e and 6e), seven grams of water are lost almost rapidly after the gas flow is turned on, as noted by the digital balance reading. In the 90°C cases (Figs. 7e and 8e), approximately fifteen grams of water are lost right after start of the gas flow. The main reasons could be:

i) The flow rate, which could fluctuate even with a servo-valve regulator.

ii) Water in glass beads at higher temperatures generally have low surface tension, thereby allowing a sizeable amount of water loss almost rapidly.

iii) Some amount of water that had settled at the bottom of the test-section could have been ejected during the first few minutes when the gas flow was initiated. This area would be below the metal screen that holds the porous medium.
Overall, column drying in the heated cases is much faster than was found with the non-heated isothermal boundary. It is well known that the surface tension of water decreases when the temperature increases. As a result, the capillary pressure, which can build up the flow resistance in the porous medium, will be significantly reduced at high temperature conditions compared to what is found at lower temperatures. This will result in higher flows of liquid water and its vapor in the porous medium. At the high temperature conditions, the water will not be easily confined to the pores due to the increased internal energy. In contrast, water can be easily evaporated, and it can travel in the porous medium and any fractures present due to the strong driving force from the pressure gradients.

Gas flow rates may vary during different stages in any given experimental case, the rate being dependent upon the pressure differential within the test-section. In addition, flow rates may vary with different temperature cases.

Significant mass drops that occur very quickly after the gas flow initiation (shown by digital balance readings) in the high temperature cases is a puzzling phenomenon. On the other hand, in the room temperature cases, there seems to be a good agreement
between the digital balance readings and the calculated weight loss.

Experiments have been performed that demonstrate some aspects of sub-residual saturation with room temperature and heated boundary conditions. Measurements have been made of temperature and relative humidity in the glass bead filled test section when the nitrogen gas flows through it. More work in the future could be performed in this field to better understand the effects of temperature and flow rate on capillary pressure, evaporation and drying phenomena.
APPENDIX I

Capacitance Element Calibrations

The moisture sensors used in the experiment are a solid-state capacitance-type, which were built in our laboratory. The sensors work with sensing the changes of moisture by conductance, resulting in linear capacitance changes 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 2 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 2.5V DC input. This design will maintain excellent DC accuracy down to microvolts. The circuit output was connected to the LabVIEW data acquisition system for automatic monitoring.

The capacitance element sensors were calibrated by the following procedure:

1). A quantity of Lithium Chloride is placed in the bottom of a container to a depth of 4 cm. In Sodium Chloride and Potassium Sulfate tests, the depth of the salts would be 1.5 cm.
2). Water is added in 2 ml. increments, stirring well after each addition. Free liquid would be seen after sometime, showing the salt's inability to absorb any more water.
3). The container is closed and about an hour is allowed for temperature stabilization.
4). Equilibrium relative humidity values are noted for the tests involving the three different aqueous salt solutions.

The measured relative humidity values were plotted versus the voltage reading and curve fitted using a linear equation. The resulting equation was used in the data collected from the experimental run to generate the moisture content plot.
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 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 a 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 different channels. SCXI-1100 is a module for signal conditioning of thermocouples, volt, and millivolt sources.
APPENDIX III

Coefficient of Permeability via 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, \( Q = k_T i A \), where \( Q \) is the flow rate of water through a porous medium of cross-sectional area \( A \), \( k_T \) is a constant known as the coefficient of permeability, and \( i \) being the imposed gradient (slope). \( k_T \) indicates the ease with which a fluid passes through a porous medium. The falling head method is one of the general laboratory methods that are available for determining the coefficient of permeability of a porous medium. The coefficient of permeability is necessary to determine the time for fluid to travel between two points within the medium. This method is direct and accurate to within about one order of magnitude.

A falling-head permeability test was run using the standard compaction mold permeameter. The permeameter consists of a standpipe, top cap with rubber gasket and inlet orifice, test mold porous stone at the base, and outlet drain hose. 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, while the time required for a certain quantity of water to pass through the specimen was recorded. The actual procedure, step-by-step, is shown below:

1. The permeameter test mold with the base plate and gasket attached was weighed.
The inside diameter and length of the test mold were noted.

2. A dry sample of glass beads was placed in the test mold and compacted to a reasonable density. The filled test mold along with base plate and gasket attached was weighed and the density of the sample was determined.

3. The sample was saturated with water while the outlet tube was open. The specimen was assumed to be saturated when water in the inlet tube on top of the permeameter mold reached equilibrium with water exiting the mold.

4. The outlet tube was clamped after the specimen was saturated. 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 elapsetime 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]

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

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

\[ a = \text{cross-sectional area of standpipe, m}^2 \]
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 of water at 24°C to that of water at 20°C was 0.9095 [Liu and Evett, 1990].

Falling Head Data Sheet

<table>
<thead>
<tr>
<th>Sample Dimensions: D = 3.30 cm</th>
<th>Area = 8.55 cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of beads + pan initial = 941.9 g</td>
<td>Height = 7.10 cm</td>
</tr>
<tr>
<td>Mass of beads + pan final = 1037.6</td>
<td>Volume = 60.73 cm³</td>
</tr>
<tr>
<td>Mass of the sample = 95.7 g</td>
<td>Density = 1.576 g/cm³</td>
</tr>
<tr>
<td>Area of standpipe = 0.40 cm²</td>
<td>Temperature = 24°C</td>
</tr>
</tbody>
</table>

Test data

<table>
<thead>
<tr>
<th>Test no.</th>
<th>h₁ cm</th>
<th>h₂ cm</th>
<th>t, sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\begin{align*}
\kappa_T &= \frac{0.4 \times 7.1}{(8.55 \times 28.3)} \ln(39.5 \times 16.7) = 0.00989 \text{ cm/sec} \\
\kappa_{20} &= \alpha \kappa_T = 0.9095 \times 0.00989 = 9.0 \times 10^{-5} \text{ m/sec}
\end{align*}

The following equation was used to determine the permeability:

\[ K = \frac{k_{20} \mu}{\rho_{H_2O} g} \]

where, \( K \) = permeability, m²

\( k_{20} \) = coefficient of permeability at 20°C, m/s

\( \mu \) = viscosity of water, N s/m²

\( \rho \) = density of water, kg/m³

\( g \) = acceleration due to gravity, m/s²

Then the permeability is

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


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