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Abstract

Nitrogen gas has been used in experimental studies related to understanding issues in the extension of multi-phase models to sub-residual saturation conditions during drying. Two different flow rates of 1 SLPM and 0.5 SLPM with a room temperature boundary condition on the aluminum column have been examined. Information about variations of humidity and temperatures is given. It is shown that the situation that exists in the experiments is somewhat different than that found in typical assumptions made by numerical modelers.

Work planned for the next quarter is outlined. The apparatus used for the work noted above will be supplemented to allow other temperature conditions than ambient to be evaluated. Temperatures up to 90°C will be used.

Other work planned for the next period will involve the use of small-scale simulated repository experiment to determine temperatures and humidities around a horizontal heater within an annulus in a rigid porous medium. The effect of backfill on performance when episodic flows are encountered will be compared to results when backfill is not present (the latter results have been determined earlier).

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Overall Project Comments

During much of this quarter the project was out of funds, awaiting the formal approval of the FY95 funding. The year's period with FY94 funding had ended. This lack of funding greatly hindered progress on the work reported and that might have been accomplished. Near the quarter end, some temporary (bridging) funding was approved within the University to continue this work because it had been indicated that this project would ultimately be approved for additional funding.

The lack of funding was not the only problem faced. We have had considerable hardware difficulties with our data acquisition system. In fact we have exchanged several components with the manufacturer in an attempt to have a fully operational system built around our Macintosh computer. Most of these problems have now been resolved.

A Study of the Extension of Multi-Phase Models to Sub-Residual Saturation

In an element of the Yucca Mountain Site Characterization Plan, engineers and scientists expressed the belief that strong capillary forces can draw water into the pores of unsaturated rock. Additionally they expressed the belief that water travels slowly in the unsaturated rock if water is confined to the pores. It was further thought that the capillary forces would keep water from dripping into the repository. It has also been understood that water will eventually (perhaps in tens of thousands of years) get into the repository, dissolve radionuclides, and reenter the flow in the mountain. The time frame may be significantly less than that based upon our work.

We have shown that predicted humidity values can easily be underestimated in the sub-residual situations when the capillary pressures are arbitrarily fixed to a maximum value by the numerical modelers. The temperature in the near-field of repository can easily be increased up above the water boiling point due to the large thermal load from the spent fuel. The high temperature profiles can cause a very important dry-out and rewetting impact on the residual and sub-residual saturations within the drift. The water will not be easily confined to the pores at the high temperature condition. In the contrast, it can be easily evaporated and transported in the porous medium and fractures due to the strong driving force from the pressure gradients.

Multi-phase transport in porous media at sub-residual saturations is of considerable importance in various applications including performance studies of the high-level radioactive waste repository, decontamination of hazardous waste sites, wood drying processes, and several other drying applications. The majority of the work performed in hydrogeologic modeling has been confined to isothermal studies and/or at liquid saturations well above residual levels. Recently, the problem of contaminant transport in the sub-residual regime has attracted considerable attention, particularly when dealing with the disposal of high-level radioactive waste in an underground repository. As a consequence, it is of importance to understand the drying effects of residual water in porous media. The capillary pressure within the porous medium is a function of thermal gradients present. This study is focusing on the possible limitations of applying multi-phase flow models to the hydrothermal processes occurring when the liquid saturation falls below residual levels.

An experimental program in our laboratory continues to study the drying effects of residue water in porous media. A flow of nitrogen gas through a porous medium (quartz beads) is used to determine the physical relationship between the liquid saturation, capillary pressure, and temperature from experimental measurements. Two cases have been examined, one using a low flow rate of nitrogen and the other using a high flow rate of nitrogen, both with an isothermal boundary condition on the test section, have been examined. These results may give useful information for numerical modelers. To furnish data to support numerical modelers in evaluating their results is the main task of this experiment.

The experimental setup is shown in Figure 1. The details of the test section is shown in Figure 2, and this is a redesigned configuration from an earlier one.

As currently used, the test section is constructed of a 16" long aluminum cylinder that has an inside diameter of 1.5" and two windows (0.275" x 5.625"). Aluminum material was chosen for this application because it is rust resistant and it has a high thermal conductivity. A constant heat flux or fixed temperature boundary condition can be applied on the outside of the aluminum wall with an appropriate experimental setup. Quartz beads with an average diameter of 0.037" are used as the fill material in the test section for all work reported here.

Nitrogen gas has been used as a displacing fluid and water was the displaced fluid in the quartz beads. Industrial grade nitrogen gas has been used. The mass flow rate of nitrogen gas is controlled by a servo valve/feedback control system. The mass flow rate data are recorded using digital signal conditioning and data

acquisition devices. The flow controller has a $\pm 1\%$ accuracy, based on the full range of 1 SLPM.

Figure 1. Diagram of piping and instrumentation used in the drying experiment.

Two relative humidity sensors are used to measure the inlet and outlet water moisture content of the nitrogen. Calibration of the humidity sensors as a function of water content and temperature has been done following the appropriate ASTM method. During the tests, the output voltages of the humidity sensors are recorded as a function of time.

Other instrumentation used includes a small-range differential pressure transmitter for measuring the pressure drop across the porous medium. The output voltages from the transmitter have been recorded. This differential pressure transmitter has a 0.5" water maximum range and a $\pm 1\%$ accuracy.

Figure 2. Schematic diagram of the test section used in the drying experiments. Two windows on one side allow visual observations during the test runs. The test section can be operated with or without heating. In the tests reported here the aluminum is kept at essentially isothermal at the ambient temperature.

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.

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. Comparisons are made between the change of water content in the test section inferred from the mass flow of water out (estimated from the air mass flow and humidity measurements) with readings taken from the digital balance. This adds redundancy to the experimental measurements. The digital balance has a 12 kilogram capacity, a 0.1 gram readability, and a $\pm 1\%$ accuracy. Room temperature and atmospheric pressure have also been measured. A computer with a LabVIEW data acquisition system has been used to collect all data from the experiment.

Tests begin at the residual saturation condition and continue until steady-state conditions are reached, which may or may not find a completely dried porous medium.

Two experimental studies have been implemented. One is with a lower mass flow rate of nitrogen gas, $Re=0.434$ (based upon the quartz bead diameter), and with a room temperature boundary condition on the test column. The other one is with a higher mass flow rate of nitrogen gas, $Re=0.8675$, with an isothermal boundary condition on the test column at the room temperature. The Reynolds numbers of 0.8675 and 0.434 are in the Darcy flow region.

(1) $Re=0.8675$ with an isothermal boundary condition

The relative humidity at the inlet and outlet vs. time is shown in Figure 3. The outlet relative humidity value maintains a constantly high value throughout most of the test. At approximately 8 hours from the completion of the test, the relative humidity started to decrease markedly. The inlet relative humidity remained approximately constant during the whole test.

A maximum of 10% discrepancy in the mass balance calculation compared to the balance measurement has been found. The comparison is shown in Figure 4.

The temperature at each location of the test section is shown in Figures 5-14. Figure 5 shows the room temperature is not strictly a constant value, but is nearly so. The nitrogen inlet temperature is shown in Figure 6, and this shows very small variations. In this test, a big temperature drop, associated with localized drying phenomena, is found in Figures 7-14. This relatively high temperature drop is due

to the cooling associated with the high mass flow rate of nitrogen gas. Figure 14 shows the outlet nitrogen temperature. This temperature decreases gradually while sub-residual conditions exist and increases back quickly to the inlet nitrogen temperature when totally dry conditions develop. The effects of the evaporation phenomena in the test column can be seen in these figures. The heat of evaporation is supplied by the enthalpy of the gas around the glass beads which causes a temperature decrease in the test column. An average of the temperature drops range from 6 to 10°C when evaporation occurs.

(2) $Re=0.434$ with an isothermal boundary condition

The relative humidity at the inlet and outlet vs. time is shown in Figure 15. The outlet relative humidity value maintains a constant value throughout most of the test. At approximately 10 hours from the completion of the test, the relative humidity started to decrease significantly.

The mass balance is a key part of our experimental plan. An estimate of the weight of the test section is calculated using the data for the inlet and outlet humidities and mass flow rate of nitrogen gas. The weight of moisture exiting with the nitrogen flow is numerically accumulated with respect to time. A digital balance is used to read the actual weight loss of the test with respect to time. Figure 16 shows a maximum of 10% discrepancy in the mass balance calculation compared to the balance measurement, and this value occurred only for a short time.

The temperature variations at each location of the test section are shown in Figures 17-26. Figure 17 shows the room temperature is nearly constant. Since this parameter has a large impact on the temperature of both the incoming gas and the wall of the test vessel, it is clearly important. Figure 18 shows that the inlet nitrogen gas temperature is maintained at a nearly constant value. Figure 19 shows there is no temperature drop at the location of thermocouple 2 due to the low flow rate. Figure 24 shows the temperature at thermocouple 7 experiences a significant drop. It decreased and increased very gradually compared to the other locations. In this test, an isothermal condition is not reached even when a small Reynolds number has been applied. Each thermocouple shows a drop of about 4 to 6°C when evaporation occurs. A smaller mass-flow-rate test is planned for the future.

Figure 3. Relative humidity at inlet and outlet vs. time ($Re=0.8675$).

Figure 4. Amount of water transported from the experiment is compared from estimates using humidity measurements and balance measurements ($Re=0.8675$).

Figure 5. Room temperature vs. time ($Re=0.8675$).

Figure 6. Nitrogen gas inlet temperature vs. time ($Re=0.8675$).

Figure 7. Temperature at thermocouple 2 (see Figure 2) vs. time ($Re=0.8675$).

Figure 8. Temperature at thermocouple 3 (see Figure 2) vs. time ($Re=0.8675$).

Figure 9. Temperature at thermocouple 4 (see Figure 2) vs. time ($Re=0.8675$).

Figure 10. Temperature at thermocouple 5 (see Figure 2) vs. time ($Re=0.8675$).

Figure 11. Temperature at thermocouple 6 (see Figure 2) vs. time ($Re=0.8675$).

Figure 12. Temperature at thermocouple 7 (see Figure 2) vs. time ($Re=0.8675$).

Figure 13. Temperature at thermocouple 8 (see Figure 2) vs. time ($Re=0.8675$).

Figure 14. Temperature at thermocouple 9 (see Figure 2) vs. time ($Re=0.8675$).

Figure 15. Relative humidity at inlet and outlet vs. time ($Re=0.434$).

Figure 16. Amount of water transported from the experiment is compared from estimates using humidity measurements and balance measurements ($Re=0.434$).

Figure 17. Room temperature vs. time ($Re=0.434$).

Figure 18. Nitrogen gas inlet temperature vs. time ($Re=0.434$).

Figure 19. Temperature at thermocouple 2 (see Figure 2) vs. time ($Re=0.434$).

Figure 20. Temperature at thermocouple 3 (see Figure 2) vs. time ($Re=0.434$).

Figure 21. Temperature at thermocouple 4 (see Figure 2) vs. time ($Re=0.434$).

Figure 22. Temperature at thermocouple 5 (see Figure 2) vs. time ($Re=0.434$).

Figure 23. Temperature at thermocouple 6 (see Figure 2) vs. time ($Re=0.434$).

Figure 24. Temperature at thermocouple 7 (see Figure 2) vs. time ($Re=0.434$).

Planned Work during Next Period

(1) Dehydration experiments with heated gas and boundary

Tests are planned using the apparatus described above to evaluate performance at elevated temperatures. Two heaters with separate feedback temperature controllers will be used in the heating process to increase the inlet nitrogen gas temperature and to maintain a constant test section elevated temperature. Different bed/gas temperatures up to 90°C will be investigated.

Figure 27. A front-view schematic of the experimental setup to simulate some aspects of flows around an underground repository. The dimension into the page is 1.5 in.

(2) Flows with heat transfer in a simulated repository drift with backfill

Backfill is one possible design in the emplacement drift that is being considered by the engineering group of the YMSCP. It is important to assess the effects of backfill in the drift under the coupling influences of heat flow and

hydrology. Backfill may divert the dripping water from the near-field and waste packages, and thereby extend a long-term low humidity around the waste packages. Therefore, the backfill design may have a better corrosion controlled in the waste packages than the non-backfill design.

Figure 28. Schematic location of the thermocouples and humidity sensors in the repository flow experiments.

It will be of interest to study the effects of humidity in the backfill and near the heater. A modification of an apparatus employed in earlier experiments will be used for these experiments. Silica sand and tuff will be selected as the backfill materials. The location of humidity sensor in the backfill will be reselected to measure the moisture presence. Figure 27 shows a rigid porous medium approximately 1.5" x 12" x 12" (high) that was prepared with a 1.5" hole through the thin dimension of the medium. A 1" diameter, 1.5" long 500 W electrical cartridge heater was installed horizontally through the medium. A ceramic insert will be used to seal both sides of the air annulus, to contain the backfill, and to support the heater.

Thermocouples are to be inserted into the medium from the large surface side. Nine and twenty-three 30 gauge K-type thermocouples will be used to measure the temperatures in the backfill and the porous medium structure, respectively. Two capacitance humidity sensors will be used to measure the humidities in the porous medium and in the backfill. The configuration of thermocouples in the porous medium is shown in Figure 28. The sides of the porous medium are sealed so that moisture cannot escape through those surfaces. The permeability of the porous media structure is about $5.54 \times 10^{-11} \text{ ft}^2$. Of particular concern is the determination of the temperatures near and in the backfill, and the humidity in the backfill. Data will be logged on a personal computer using LabVIEW software and hardware.