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"HEAT TRANSFER STUDIES"

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Abstract

Work continued from last quarter related to studies of heat transfer and fluid flow in porous media. One experiment focused on issues of drying in subresidually-saturated systems. The other experiment deals with studies of flows in a repository-like geometry around a heated horizontal annulus.

In the subresidual saturation studies, elevated temperature environments were considered during this quarter. A 1"x 8' long heating tape (heating capabilities of 8.6 W/in²) with an on-off type temperature controller has been used to maintain a constant temperature on the aluminum test section (the latter has been described in earlier reports). Nitrogen gas with a flow rate of 1 SLPM was flowed through a glass-bead medium with an isothermal (90°C) boundary condition. The drying characteristics of this system are reported.

In a second experiment, that of flow and heat transfer around a simulated drift, a low, constant heat flux boundary condition on the heater has been used. Two different admitted water quantities, 200 ml and 300 ml, have been used as before. The response of temperatures and relative humidity in the porous medium and annulus are very similar to the results of the high constant heat flux on the case of 300 ml water experiments. This is not the case for the 200 ml water experiment. The low constant heat flux with a small quantity of water is found to have no significant effect on the temperature responses.

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

The high thermal load from buried high-level radioactive nuclear spent fuel can easily heat water in the near-field of the repository above the boiling temperature. It is of interest to investigate the multi-phase flow models to sub-residual saturation in the porous medium under various thermal boundary conditions. It is well known that the surface tension of water decreases when the temperature increases. As a consequence, 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 obviously result in higher flows of fluids in the porous medium which could cause more moisture to penetrate into the repository. 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.

Our studies of computational methods used in current numerical codes for determining performance estimates show that humidity values can easily be underpredicted in sub-residually saturated conditions. We suggest that capillary pressures should be carefully examined under the different boundary conditions especially in the high temperature conditions. In the past, this parameter has been arbitrarily fixed to a maximum value by computer modelers to avoid numerical divergence problems.

To address this issue, our recent studies are focusing on the limitations of applying multi-phase flow models to the hydrothermal processes occurring when the liquid saturation falls below residual levels. A variety of different thermal boundary conditions are being considered in these studies. An experimental program in our laboratory continues to analyze the drying effects of residue water in a porous media with a heated boundary on the test section. A flow of nitrogen gas through a porous medium is used to determine from experimental measurements the physical relationship between the liquid saturation, capillary pressure, and temperature.

The test section consists of a 16" long aluminum cylinder that has an inside diameter of 1.5" and two windows (0.275" x 5.625"). The reason why aluminum was chosen for this application is because this material is rust resistant and it has a high thermal conductivity. For the current studies, a constant temperature (90°C) boundary condition has been applied on the outside of the aluminum wall.

Quartz beads with an average diameter of 0.037" are used as the fill material in the test section. The glass beads have been cleaned with a 1% hydrochloride solution.

Nitrogen gas is used as the displacing fluid and water is the displaced fluid in the glass beads. A gas flow rate of 1 SLPM is used in the studies reported here. In this case, the mass flow rate of nitrogen gas yields $Re=0.8672$. This Reynolds number assures that the flow is in the Darcy region. Industrial grade nitrogen gas has been used in this study. Distilled water has been used to avoid any interferences such as any chemical bonding strength that might be caused by impurities.

Two relative humidity sensors have been used to measure the inlet and outlet moisture content of the nitrogen on a continuous basis. Prior to performing experiments, 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 (0.5" water maximum and $\pm 1\%$ 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. Comparisons are made between the change of water content in the test section inferred from integration of the mass flow of water out (estimated from the air mass flow and humidity measurements) with readings taken from the digital balance.

Thirteen 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. Three thermocouples are located on the top, middle, and bottom outside of the test section to assess the accuracy of the assumed isothermal boundary condition on the wall.

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.

A case where a heated wall has been used on the experiment is reported here. An Omega 1" x 8' heating tape (maximum output rating of 8.6 W/in²) has been chosen to accomplish the heating task. A digital balance of 12 kilogram capacity, a 0.1 gram readability, and $\pm 1\%$ accuracy has been used to measure the weight of the test section as a function of time.

A mass flow controller with a servo valve has been used to control the nitrogen gas mass flow rate through the test section. It has $\pm 1\%$ accuracy on the full range of 1 SLPM.

The experimental setup is shown in Figure 1. The details of test section are shown in Figure 2.

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

(1) $Re=0.8672$ with a heated isothermal boundary condition

This test began with the system at residual saturation. At the start of the experiment, the nitrogen flow and the wall heater were turned on. Data are reported from this starting condition.

The relative humidity at the inlet and outlet vs. time is shown in Figure 3. The outlet relative humidity value maintains a constant value throughout most of the test. At approximately 25 minutes from the completion of the test, the relative humidity started to decrease significantly. The inlet relative humidity is a constant.

The outlet relative humidity value gradually decreased throughout most of the test (after 40 minutes).

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.

Decrease in mass of the experimental apparatus with time, which is due to drying of the bed, is an important parameter in the study. Measurements from the digital balance are compared to similar 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. An average of 7.8% discrepancy in the mass balance calculation compared to the digital balance measurement has been found and it is shown in Figure 4.

The temperature at various locations in the test section is shown in Figures 5-14. Figure 5 shows that the room temperature does not remain at a constant value. The room temperature increased about 7% during the test, and this is a factor beyond our control.

Figure 6 shows the nitrogen inlet temperature. Note that the inlet temperature is lower than the room temperature. This is probably due to the fact that the room temperature increased during the test.

Figure 3. Relative humidity at inlet and outlet vs. time ($Re=0.8672$).

Temperature responses in the bed are shown in Figures 7-14. In previous tests with room temperature or insulated conditions imposed on the boundary, temperature decreases were demonstrated near the drying front. In this test, no significant temperature drop is found within the bed. The temperatures in the location of thermocouple 2 and thermocouple 9 where the glass beads are not

present shows a quick heating effect due to the convection heat transfer mechanism. Those results are shown in Figures 7 and 14, respectively.

Figure 4. Amount of water transported from the experiment is compared from estimates using humidity measurements and digital balance measurements ($Re=0.8672$).

Figure 5. Room temperature vs. time ($Re=0.8672$).

Figure 6. Nitrogen gas inlet temperature vs. time ($Re=0.8672$).

Figure 7. Temperature at thermocouple 2 (see Figure 2) vs. time ($Re=0.8672$).

Conduction heat transfer in the glass beads has a higher thermal resistance than convective effects, and thus the effect of the heated boundary is seen after some time delay from the start of the test. This lag can be seen in Figures 8-13. The temperature gradually increases even when the nitrogen gas flows through the glass beads containing the residual water. The heat of evaporation is no longer supplied by the enthalpy of the ambient gas around the glass beads. When it is, it can cause a local temperature decrease in the test column as was shown with the other boundary condition situations reported earlier. In this test, the heated isothermal boundary can deliver enough energy to furnish the heat of evaporation. Overall column drying in the heated case is much faster than was found with the non-heated isothermal boundary.

Figure 8. Temperature at thermocouple 3 (see Figure 2) vs. time ($Re=0.8672$).

Figure 9. Temperature at thermocouple 4 (see Figure 2) vs. time ($Re=0.8672$).

Figure 10. Temperature at thermocouple 5 (see Figure 2) vs. time ($Re=0.8672$).

Figure 11. Temperature at thermocouple 6 (see Figure 2) vs. time ($Re=0.8672$).

Figure 12. Temperature at thermocouple 7 (see Figure 2) vs. time ($Re=0.8672$).

Figure 13. Temperature at thermocouple 8 (see Figure 2) vs. time ($Re=0.8672$).

Figure 14. Temperature at thermocouple 9 (see Figure 2) vs. time ($Re=0.8672$).

A Study of Unsaturated Flows with Heat Transfer in a Repository Drift

The experimental design described in the previous report has been used to investigate the effect of water flow through a rigid porous medium with heat transfer around an annulus. Figure 15 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, forming an annulus in the hole. A ceramic insert was used to seal both sides of the annulus and to support the heater in the annulus.

Figure 15. 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.

Thermocouples are inserted into the medium from the large surface side. Nine and twenty-three 30 gauge K-type thermocouples are used to measure the temperatures in the annulus and the porous medium structure, respectively. Two capacitance humidity sensors are used to measure the humidities in the porous

medium and in the annulus. The configuration of thermocouples in the porous medium is shown in Figure 16. 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 annulus, and the humidity in the annulus. Data are logged every 10 seconds on a personal computer using LabVIEW software and hardware.

Figure 16. Schematic location of the thermocouples and humidity sensors in the repository flow experiments.

An experimental run begins with a dry porous material and a low constant heat flux (i.e. 14.5 V and 0.46 A) on the heater. In this report, studies of a constant heat flux condition are reported that yields a low heater temperature ($\approx 150^\circ\text{C}$) in the dry condition. Tap water at ambient temperature is introduced from the top of the porous medium when a steady state dry condition in the porous medium and air annulus is reached. With constant heat flux conditions, the heater temperature does not remain constant when water and/or vapor penetrates into the air annulus.

The effect of water quantity on the response of the constant heat flux system is investigated. Experiments were performed using 200 ml or 300 ml water being poured onto the top of the 12" x 1.5" surface.

Figure 17. Variations of temperature and relative humidity in the air annulus with a constant heat flux and 300 ml of water flowing through the system.

Figure 17 shows the variations of temperature and relative humidity in the air annulus with a constant heat flux from the heater with a large (300 ml) quantity of water. The temperatures in the annulus and on the wall of the annulus have different responses when moisture reaches those points. Heater temperature increases from 152°C to 270°C while moisture stays in the annulus. It decreases drastically back to the steady-state condition when the drying process starts. Thermocouples 1, 2, 3, and 5 indicate that the temperatures are higher than the water boiling point when moisture reaches there. They also show a small fluctuation when moisture reaches there and indicate temperatures decrease to a saturated steam temperature value. The relative humidity in the annulus is almost 100% when steam penetrates the annulus and it has an average value of 80% in annulus before the drying is completed. The thermal impedance effects to the moisture flow are no longer strong enough to keep moisture away from the annulus. The system needs about an hour to return to steady state conditions at

approximately the same temperature as existed before water admission. The water boiling point is about 98.5°C, and this is measured during the test.

Figure 18 shows variations of temperature at a 5 in height within the porous medium, which is 0.25" above the rim of annulus. As noted above, these results are for a constant heat flux on the heater and 300 ml water admitted to the top of the porous medium. The temperatures remain almost at constant values before the water vapor reaches those points. These temperatures did not drop very much when water flowed through those points because of a heating effect to these points from the top of the porous medium. Thermocouple 19 has experienced increased and decreased temperatures within a short time, and these increased again with a small slope then decreased to 67°C for 90 minutes. The locations of thermocouples 17 and 21 showed decreased and increased temperatures, respectively, when water flowed through these points. From this result, a non-uniform heating effect from the water vapor has occurred. This may be due to differences in the flow paths on each side because of phase change taking place. Thermocouples 17, 18, 19, 20, and 21 show temperatures below the boiling point when water flowed through. A phase change apparently occurred at the locations of thermocouples 17, 18, 19, 20, and 21. A mixed heat transfer mechanism of convection and conduction could be substantiated.

Figure 18. Variations of temperature at a 5" height in the porous medium with a constant heat flux and 300 ml of water.

Figures 19 shows variations of temperature at a 5.5 in height in the porous medium with a constant heat flux and 300 ml of water. Thermocouple 15 shows a fluctuating response when cool water is admitted from the top. Thermocouple 16 shows a temperature increase and thermocouple 14 shows a temperature decrease when the water flowed through. It should be noted that the temperatures on the left hand side of the center of porous medium structure experienced a drop in temperature when the water flowed through. But the temperatures on the right hand side showed an increase. Refluxing phenomena may be occurring in these regions as shown in the temperature fluctuations at thermocouple 15. This observation is different from the low heater temperature (110°C) experiment with this same amount of water admitted.

Figure 19. Variations of temperature at a 5.5" height in the porous medium with a constant heat flux and 300 ml of water.

Figure 20 shows variations of temperature at the left hand side of the annulus with a constant heat flux and 300 ml water. Thermocouple 24 is located in the porous medium 0.25" to the left of the rim of the annulus. Its temperature remains at a constant value (below the water boiling point) before water admission from the top of porous medium. When water flows through this point, the region around thermocouple 24 contains saturated water. This region then dries out and temperatures return back to their steady state values. Thermocouple 23 shows a

similar behavior to this. Readings from thermocouple 23 remained at a constant value which is below the water boiling point before the water vapor reached this point. The reason why the temperature did not drop first when the water flowed through this point could also be explained by a heating effect from the top of the porous medium to that point. This was apparently followed by some liquid being evaporated, and this caused the temperature to decrease. The net result yielded a temperature about 4°C below the steady state temperature. A complicated heat transfer mechanism of conduction and convection probably took place, but the convection heat transfer dominates in the refluxing region. Thermocouple 22 has a similar response to that shown for thermocouple 23.

Figure 20. Variations of temperature at the left hand side of air annulus with a constant heat flux and 300 ml of water.

Figure 21 shows variations of temperature at a 3 in height in the porous medium with a constant heat flux with 300 ml water. Thermocouple 29 shows that this location in the porous medium heats up to below the boiling point for a very short time and then a cooling effect occurs at this point when the low temperature moisture reaches there. Thermocouples 28 and 30 also indicate that temperatures are below the boiling point. The fluid is apparently heated up when it travels through and around the annulus. Thus, it causes a small heating effect in the regions of thermocouples 28 and 30. The temperatures at thermocouples 28 and 30

after the cooling effect occurred gradually approached the steady state temperatures again.

Figure 21. Variations of temperature at a 3" height in the porous medium with a constant heat flux and 300 ml quantity of water.

Figure 22. Variations of temperature at a 8" height in the porous medium with a constant heat flux and 300 ml of water.

Figure 23. Variations of temperature at a vertical top the porous medium with a constant heat flux and 300 ml quantity of water.

Figure 24. Variations of temperature at a vertical bottom the porous medium with a constant heat flux and 300 ml of water.

Thermocouples 10, 11, and 12 all demonstrate the same kinds of responses due to fluid cooling effects on these regions. Figure 22 shows variations of temperature at a 8 in height in the porous medium for the constant heat flux with 300 ml water.

Figure 23 shows the variations of temperature at a vertical top in the porous medium with a constant heat flux and 300 ml water. Figure 24 shows variations of temperature in a vertical line directly below the center of the annulus with a constant heat flux and 300 ml water. Thermocouples 29, 31, and 32 in Figure 24 indicate that temperatures increase for a short period of time. The temperature then slowly decreases as the medium dries. A similar response, but lower in temperature overall, is shown for thermocouple 32.

Figure 25. Variations of temperature at a 5" height in the porous medium with a constant heat flux and 200 ml of water.

Figure 25 shows variations of temperature at a 5 in height within the porous medium, which is 0.25" above the rim of the annulus, when a constant heat flux and 200 ml water are present. The temperatures remain almost at constant values except at the locations around the thermocouples of 20 and 21. This is a very bizarre

phenomenon. These results are quite different than was found in tests with other boundary conditions. Four tests with the same conditions have been conducted, and the same results have been found each time. Time-fluctuating temperatures are found on the right hand side of the porous medium structure (thermocouples 20 and 21), but temperatures remain almost constant on the left hand side.

Figure 26 shows variations of temperature at a 5 in height within the porous medium, which is 0.75" above the rim of the annulus, when a constant heat flux and 200 ml water is present. The temperature on the right hand side of the porous medium structure, the thermocouple 16, shows a time-fluctuating effect. This type of variation is not seen on the left hand side of the apparatus.

Figure 26. Variations of temperature at a 5.5" height in the porous medium with a constant heat flux and 200 ml of water.