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Progress Report
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"Heat Transfer Studies of Waste Repository Design"
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MAIN TASK: VISUALIZATION METHODS IN HEAT TRANSFER THROUGH POROUS MEDIA

A study of the phase change phenomena in porous media using Christiansen filters continues in order to determine the experimental conditions most favorable to the use of this method. A calibration setup has been finished. Determination of the wavelength corresponding to the equality of the refractive indices varies with temperature is going to be carried out later. The dispersion curves of the solid and liquid phases constituting a transparent saturated porous medium generally have different slopes. It is thus impossible to achieve the equality of the refractive indices for all wavelengths simultaneously. For a given temperature, the dispersion curves intersect at a point corresponding to a single wavelength. From our investigation, we have found that we need to change the liquid phase material, ethyl salicylate ($HOC_6H_4COOC_2H_5$), what we have proposed before. This is because the boiling point of ethyl salicylate is too high for our purposes (about 233°C). Therefore, it is not a suitable material to do the phase change study in the Christiansen filters.

A suitable liquid phase organic chemical material for our research must fit in the following criteria:

- Its refractive index should close to 1.51 (the value of the refractive index of the soda-lime glass beads which we are using for the solid phase).
- The boiling point should not be too high so that the commercial mica cartridge heater can provide the maintain phase change conditions within the cell.
- It should be a non-toxic or very low toxicity organic chemical material.
- It needs to be a clear and colorless liquid.
- It has to have a high index of refraction.

- It should be a non-reactive chemical liquid material with metal, air, and water vapor.
- It needs to be non-flammable and non-explosive.
- It should be highly stable organic chemical material.
- Its cost should not be too prohibitive.

We have found that tetrachloroethylene ($Cl_2C=CCl_2$) might be a satisfactory and suitable organic chemical material. Its refractive index is 1.509 at 25°C, and its boiling point is 121°C.

A few chemicals have been used in the earlier studies of the single phase (i.e. below the boiling points of the organic chemical liquids) Christiansen filters by Klarsfeld et al. [1] and Raman et al. [2,3]. One example is chlorobenzene (C_6H_5Cl) with a refractive index of 1.5216 at 25°C and a boiling point of 131.6°C. The volatility and flammability characteristics of chlorobenzene are the disadvantages that need to be considered carefully in our experimental study. Its vapor is also very harmful. Benzyl alcohol ($C_6H_5CH_2OH$), its refractive index is about 1.5385-1.5405 at 20°C and the boiling point is about 206°C which is too high to use it. Nitrobenzene ($C_6H_5NO_2$) is a yellow, oily liquid and poisonous. The mixture of carbon disulfide (CS_2) and acetone (CH_3COCH_3) has also been used in Christiansen filter experiments in the past years. The boiling point of this mixture liquid is low (about 50°C), but carbon disulfide is a very poisonous and extremely flammable chemical. In addition, acetone is also an extremely flammable liquid which gives us a drawback for our work. Benzene (C_6H_6) has a refractive index in the range 1.515-1.517 with a boiling point about 80.1°C. Because it has been designated as a carcinogen that is toxic, narcotic, extremely flammable, and poisonous, we decided to avoid using it. Anisole or methylphenyl ether ($C_6H_5OCH_3$), bromotrichloromethane (CCl_3Br), n-butyl phenyl acetate ($C_4H_9OOCH_2C_6H_5$), isopropyl iodide (CH_3CHIH_3), mercaptoethanol ($HSCH_2CH_2OH$), para-methyl anisol ($CH_3C_6H_4OCH_3$), methyl benzoate ($C_6H_5CO_2CH_3$), ethyl iodide (CH_3CH_2I), glycol dimercaptopropionate ($HSCH_2CH_2COOCH_2$-)$_2$, para-chlorotoluene ($ClC_6H_4CH_3$), cuminic alcohol ($CH_2OHC_6H_4CH(CH_3)_2$), and 1-phenyl butene-

2 ($C_6H_5CH_2CH{=}CHCH_3$) have broadly been examined for our research, but we could not find a suitable chemical other than tetrachloroethylene.

A number of papers have also been reviewed. Among other details, these indicate that the transmission coefficient of a Christiansen light filter is an exponential function [2] which involves five important variables, (a) the wavelength of the light, (b) the thickness of the cell, (c) the size of the individual particles of the porous medium, (d) the difference between the refractive indices of the medium and the surrounding liquid, and (e) the proportions of the volume of the cell occupied respectively by the liquid and by the porous medium. Thus, we need a tunable laser to give us a variety of wavelengths that correspond to the equality of refractive indices as we heat the cell up to the liquid's boiling point. Argon lasers (as we are using) generally emit several wavelengths in the visible spectrum and are used in spectroscopy and as pumping sources for dye lasers.

Christiansen Filters do not work well in three-dimensional thermal fields. Hence, we must attempt to develop a nearly two-dimensional experiment.

The spectral character and intensity of the transmitted light in the Christiansen experiment is influenced by several factors, of which the thickness of the column through which the light filters is of particular importance. The emerging light from the cell will be attenuated too much if the cell thickness is too large. Then it will certainly affect the ability to achieve satisfactory visualization results. As reported in an earlier summary, our calibration test cells have three different thicknesses (i.e. lengths): 2 inches, 4 inches, and 6 inches. The actual Christiansen Filter cell we have built has a thickness of 2.5 inches.

A transparent isotropic solid is placed inside a flat-sided cell of glass, and the latter is filled up with a liquid of which the refractive index is adjusted to equality with that of the powder for any desired wavelength, which the rest of the spectrum is not transmitted but only diffused in its passage through the cell. A few different kinds of solid phase particles have been used by Raman without applying any phase change. For instance, hexamethylenetetraamine (HMTA, i.e. $(CH_2)_6N_4$), also known as hexamine or urotropin, is inexpensive, readily available, and a colorless powder. But it has

an irritating action on the skin and is flammable. Potassium chloride (KCl) has also been used as the solid phase material which is a colorless or white crystal or powder. Barium sulfate ($BaSO_4$) can also be used successfully in a cell from five to ten millimeters thick with carbon disulfide as the interstitial liquid. Precipitated calcium sulfate ($CaSO_4$) in the form of gypsum also gave good results, the appropriate liquid in this case being chlorobenzene. Magnesium fluoride (MgF_2) also worked well; the appropriate liquid to use in this case is acetone.

Three different sizes of soda-lime glass beads have been adopted in our study: 2mm, 3mm, and 10mm in diameter. In the practical use of a Christiansen filter, it is necessary, among other things, to separate the light directly transmitted by the filter from that which is diffused or scattered by it. The characteristics of the diffraction halo has an important bearing on this matter. It is not simply a matter of geometrical optics. The diffraction effect has its origin in the same set of circumstances which determine the spectral range of the regularly transmitted light, namely, the optical heterogeneity of the medium and its variations with wavelength. The halo is, in essence, a superposition of the diffracted radiation having its origin in the successive layers within the cell traversed by the incident beam of light. In considering the problem of the distribution of light in the halo and the spectral character of the radiation composing it, it should be emphasized that the diffracted radiation has its origin at the layers parallel to the wave-front traversed by it, and hence that it represents the combined effect of all the particles in a layer. In other words, we have to consider the configuration of the whole wave-front after it has traversed the layer. That is, the positions of the individual particles in the layer would determine the locations of the elevations or depressions (as the case may be) on the wave-front, while the size and shapes of the particles and the difference between the values of the refractive indices of the solid and liquid for the particular wavelength would determine their magnitude. The nature of the results to be expected in our research would necessarily be somewhat modified by various considerations. Firstly, the diffracted radiation would be absent for the wavelength of maximum transmission for which the refractive indices of materials encountered by the ray are the same values at the certain

temperature. The radiation transmitted would rapidly increase in intensity as the differences become numerically larger and attain large values, but provided the differences are not too large, they would be concentrated principally in directions adjacent to that of regular transmission. In this case, the angular separation is determined by the average separation distance of the individual particles. (In a close-packed arrangement, this would also be the size of the individual particles.) As the differences of refractive indices among the materials traversed by the ray increase beyond a certain limit, the diffracted radiation would spread out over a wider range of angles, and the direction of their maximum intensity would also move away further from that regular transmission. The ray intensity in any particular direction would simultaneously be significantly weakened. If the particles are very large, the diffracted light would appear in directions very close to that of the regularly transmitted light, and its separation from the latter would obviously become difficult to see. If, on the other hand, the particles are very small, the spectral width of the transmission would itself be greatly increased. There is an optimum size for the particles if the filters are to function most usefully.

Tetrachloroethylene is used for the liquid phase. The addition of a few drops of benzene or carbon disulfide might shift the transmission of spectrum to give better visualization results.

SUPPLEMENTAL TASK: UNSATURATED FLOW EXPERIMENT WITH HEAT TRANSFER IN POROUS MEDIA

Overview Introduction

An experimental study on heat transfer in a porous medium penetrated by a liquid is being carried out. For this work a porous medium with imbedded heat source is being used, and water flows are applied in a transient manner. As water flows vertically and approaches the heater, the heated area should cause vaporization of the water, forcing the vapor to flow horizontally. At some point the vapor will condense and water will flow

vertically again. In this way the water should be diverted around the heated area. This general phenomenon has been called "heat pipe" effect. Therefore, the determination of the temperature field is to be evaluated at several points of test sample in order to evaluate the "heat pipe" effect. Further the experiment will present a model of heat and mass transfer in an unsaturated zone of porous media, taking into account the effects of temperature gradients on the advective flux, and on the enhancement of thermal conduction. It is hoped that the experiment will give insight that describes the moisture migration in an unsaturated zone for the condition that the temperature is suddenly increased to a higher value.

Design Modification

During this quarter the equipment was set up and calibration of most of the instrumentation was done. However, during the initial testing procedure some part of the apparatus had to be modified due to some required changes in the operation. This is described in what follows.

Modification of Quartz Bead-Filled Plastic Tank

The middle part of the experiment setup is 1 X 3 X 2 ft (0.3x0.9x0.6 m) tank fabricated from a 1/2 inch Plexiglass sheet. However, during the initial testing we modified the tank size to 1x3x1 ft (0.3x0.9x0.3m) to decrease the amount of fill material that needed to be dried between runs. Drying of the original amount was a significant time-consuming process.

A second modification was done in the middle part of the tank, where a 5/8 inch (16 mm) diameter electrical immersion heater that spans the tank horizontally was mounted. During the initial testing it was noted that the heater portion in contact with wall reached a temperature higher than the melting point of the Plexiglass. To rectify this problem, a Teflon mounting plate was installed at the heater penetration. See Fig.1.

Modification of Inflow System

The inflow system is designed to give a uniform distribution of water over the fill. The system consists of a 5 gallon head tank mounted at 7 ft high on top of the main test tank, 3/4 inch plastic tubes, control valve, and set of square patterned spray nozzles. The square nozzles are mounted on a 2x4 ft plastic plate which is fitted on top of the main test tank. The only modification done in this part was to add gate valves to each pipe leading to the square nozzle which will work as valves to control the flow rate at each nozzle in order to give a uniform flow of water to the filling material. See Fig. 1 for the modification.

Outflow System

The out-flow system is composed of 1'x3'x7" plastic tank with partitions spaced approximately 3" apart. The partitions divide the bottom region into catch chambers which are used to measure the one-dimensional spacial distribution of water exiting the test tank. No modification has been done to this part.

Measurement of Moisture Content Using a Resistance Method

The use of capacitance and resistance methods for making point measurement of moisture content has carefully been studied. There are clearly commercial instruments of this type available, but we have been seeking inexpensive techniques of this type to apply to our experiments.

Our approach has been to evaluate simple two-wire configurations, with or without a spacer separating the two wires. Several experiments have been conducted to determine the optimum design of sensor configuration.

Resistance and capacitance approaches were tested over different probe configurations and with a varying distance between the probes. We have tried a few different sizes of conductor wire to make the probes. A 30 gauge conductor wire is too small use as it could be bent easily when we

insert it into the test section. A 20 gauge conductor wire is too big, causing significant channelling through the porous medium. As a compromise, a 24 Gauge conductor wire was selected to conduct the bulk of the testing.

Materials including balsa wood, plastic, glass, and rubber have been used to separate the probes. Balsa wood has the advantage of being worked easily into small shapes. However, its life in a high temperature and high moisture environment is not good. Plastic could be cut and machined to small shapes easily. And it could withstand high temperature and moisture. Glass is a difficult material to be cut into a small shape but it is a good material to hold up in the experiment's environment. Rubber would hold up to the environment and could be cut to the small sizes but it would not hold the probes with a fixed distance apart in the glass beads media due to rubber's elastic character. Therefore, plastic is selected as the spacer material. The plastic could also be bonded to the metallic wire easily with epoxy adhesive.

The insulation material of 24 gauge conductor wire is stripped about 0.0133 inches. Then the strands of the conductor wire were twisted together and tinned with a soldering gun. A piece of plastic of dimensions 0.0667 x 0.0667 x 0.1 inches is cut for the spacer. A small amount of epoxy is applied to the wires nearest the insulation. Then the plastic is set between the wires and held in the place by the epoxy. When the probe is completed, the gap between the wires measures approximately 0.033 inches.

Calibration studies showed that this probe works quite successfully for determining the presence of water (i.e., simply on or off) using resistance measurements. Precise calibration of water content vs. electrical signal out is yet just a goal. Less success has been achieved with a capacitance method using the same probes.

Boundary Condition Study

We have begun a study related to the boundary condition between an unsaturated porous medium (vertically above) and a region such as air (vertically below). Our particular interest is the penetration of water into

the air region as a function of a number of parameters. Included is the presence of a temperature gradient. Current work involves the definition of the problem, understanding of the important physics of this problem, and identification of the primary parameters. It appears that the flow problem around a region of this type has been reported in the literature (see, for example, reference 4). We have not yet been successful in finding a study specifically related to the water penetration issues.

References

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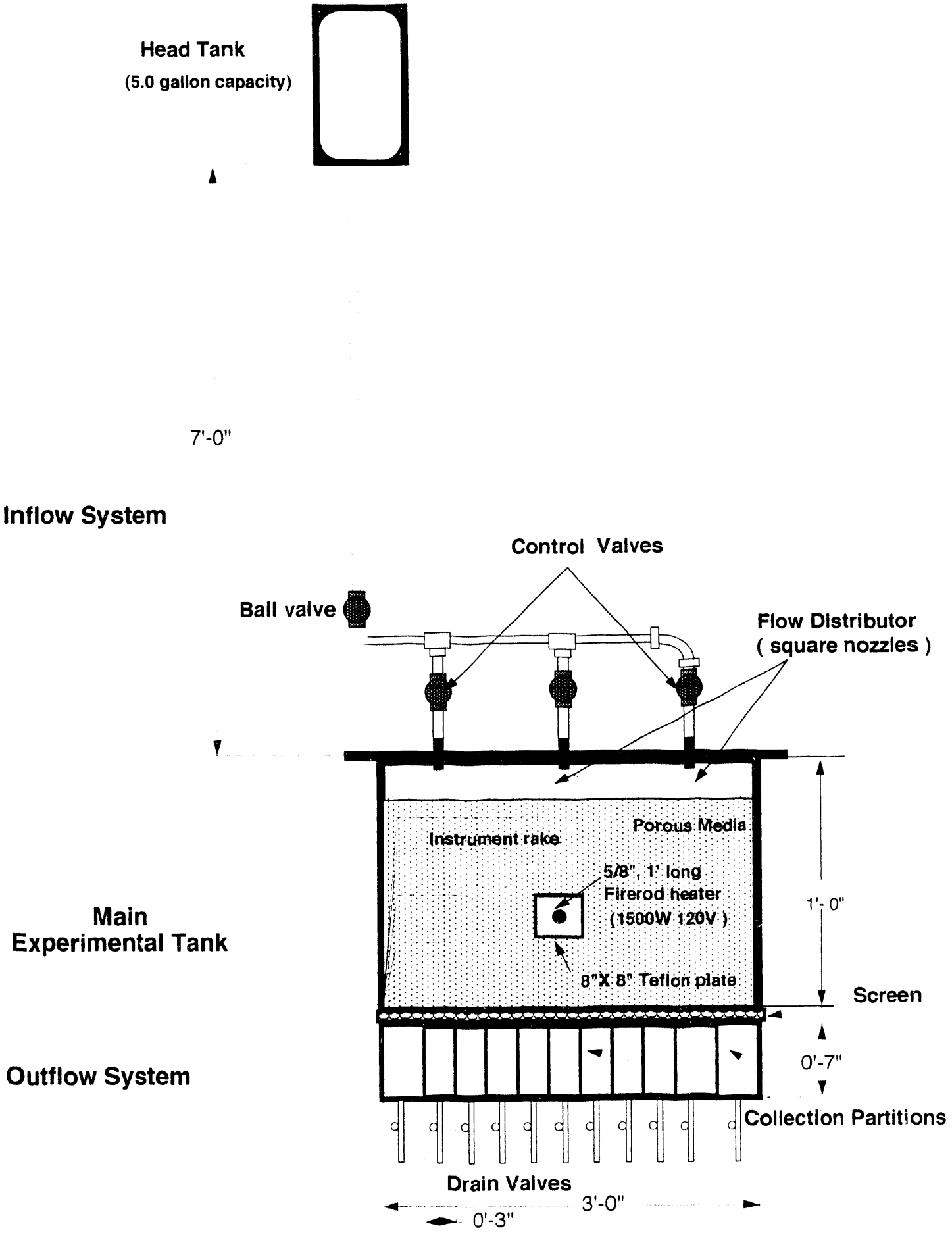

Figure 1: Complete experimental apparatus system (not to scale)

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