Experimental analysis of the freezing process in unsaturated porous media Cooled from above
(Influence of freezing temperature and initial water saturation)

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Abstract

In this paper, the freezing process in unsaturated porous media considering heat and mass transport across moving boundary has been investigated experimentally. The influences of the initial water saturation and constant temperature heat source on heat transfer and water transport across moving boundary during freezing process in unsaturated porous media are clarified in details. It is found that the rate of the absorption of water into the frozen layer depends on the freezing temperature and the water saturation at the freezing front. As a result, ice content in the frozen layer is related to the rate of water absorption and the freezing temperature. The results presented here provide a fundamental understanding of freezing process in porous media.

Keywords : freezing , unsaturated porous media, freezing front

1. Introduction

The phenomenon of solidification or freezing process in unsaturated porous media is widely encountered in nature and in many engineering systems. Some of the specific applications include pipeline transport in permafrost regions and cryosurgery, as well as in the transportation of coal in cold weather, ice accretion on vehicles and static structures, solidification of alloys, food processing, chemical processes, cryopreservation of engineering tissues, and many others. The freezing process in unsaturated porous media is an important which the fluid in unsaturated layer moves toward to the freezing front due to capillary and osmotic action. Thus, the ice content in the frozen layer is expanded between frozen and unfrozen layers.

A similar problem, that is, the simultaneous heat and mass transfer problem in porous media has been studied by many authors including Zhang and Hung Nguyen [1], Ismail and HenrõÂquez [2], Beckermann and Viskanta [3], Weaver and Viskanta [4-5], Chellaiah and Viskanta [6], Devireddy et al. [7], Lu and Zhou [8]

Up to the present time, the related problem of solidification in porous media in the absence of an unsaturated state has been investigated experimentally and numerically by many researchers and up to date reviews are available: Hashemi and Sliepcev [9], Frivik and Comini [10], Sparrow and Broadbent [11], Chellaiah and Viskanta [12], Liu et al. [13-14], lu et al. [15], Rattanadecho [16] and Dani [17]

Only a very limited amount of experimental work on phase change heat transfer in unsaturated porous media has been reported, and understanding of the phenomenon is incomplete. At macroscopic level, there exist four distinct phases (porous matrix, ice, water, and air) within any representative elementary volume of the unsaturated porous media system.

When solving a moving boundary problem, that is, freezing process of unsaturated porous media, complications arise due to the motion of the freezing interface with the phase transformation and the absorption of water at this interface. As such, the position of the interface is not known a priori, and the domains over which the energy equations are solved vary. There exists a discontinuity in the temperature gradient, as well as liquid saturation gradient at the freezing interface. Furthermore, during solidification in unsaturated porous media, the mechanism of the water transport to the interface and the growth of the segregated ice must be clearly investigated. Namely, the water in the unfrozen layer is absorbed to the interface due to capillary and osmotic actions so that ice content in the frozen layer increases, and a segregated ice layer often grows between frozen and unfrozen layers.

The purpose of this study is to report on experimental studies of the freezing process in unsaturated porous media cooled from above. We have focused on the rate of the absorption of water due to capillary action, temperature profiles, saturation profiles, freezing front and have investigated the characteristics of freezing in unsaturated porous media for the case without the transformation of porous bed(shrinkage) experimentally.

2. Experimental apparatus and procedures

This study considers the one-dimensional freezing process in unsaturated porous media cooled from above. The fluid is initial at a temperature above its freezing point, and is contained in a rectangular test cell which the bottom and side walls are insulated only the top wall is opened and is maintained at a temperature below the freezing point, as shown in figure 1.

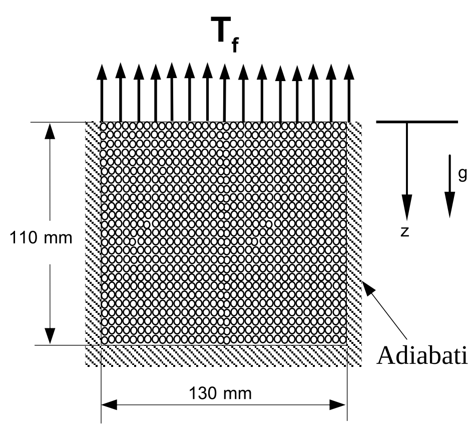


Fig. 1 Schematic diagram for the freezing processes

Figure 2 shows the experimental apparatus for freezing process analysis. A rectangular test cell with inside dimensions of 130 mm length, 110 mm height and 50 mm width. The samples are unsaturated porous media which are mixture of water and uniform size spherical glass bead with a diameter of 0.15 mm (porosity, ε = 0.385). The horizontal top wall of packed bed is contact with the heat exchanger that is connected through the cooling temperature tank. An ethylene glycol-water solution is used as the cooling medium. The test cell is covered with insulation to reduce heat loss at the walls.

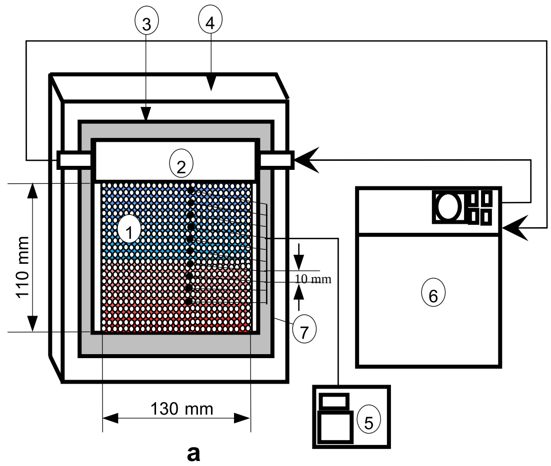
Throughout the experiments the test cell is set up in a constant temperature room held at 10 ^{o}C. The Cu-Co thermocouples with diameter of 0.2 mm are used to measure the temperature distributions inside the packed bed which are placed at the center of packed bed at each 10 mm interval. The thermocouples are connected to the data logger and a recorder through which the temperatures could be measured and store at preselected time intervals. The position of solidification interface in the packed bed is determined by interpolating the fusion temperature from the thermocouple reading.

The water or ice saturations in the packed bed are defined as the fractions of the volume occupied by water or ice to the volume of the pores. They are obtained by weighing the dry and wet mass of the sample, which is cut out in volume of about 1 cm^3 at the end of each run.

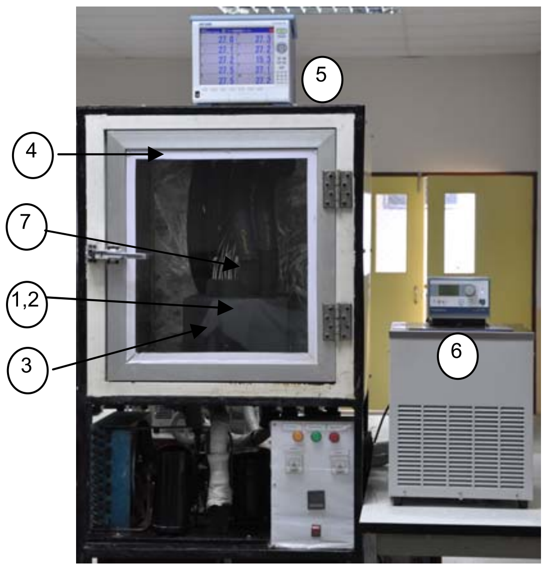
The water saturation formula can be described in the following form [16]:

$$s=\frac{\rho_p(1-\varepsilon)(m_w-m_d)}{\rho_w\varepsilon m_d} \qquad (1)$$

where s is water saturation, m_w and m_d are wet and dry mass of the sample, respectively, ε is porosity, ρ_w and ρ_p are densities of water and particle, respectively.



a



b)

1) packed bed, 2) cooling heat exchanger, 3) insulator, 4) temperature control room, 5) recorder, 6) cooling temperature tank 7) thermocouples

Figure 2. Experimental apparatus (a) equipment setup, (b) freezing measuring system

The porosity of a porous media describes the fraction of void space in the packed bed, where the void may contain, for example, air or water. It is defined by the ratio:

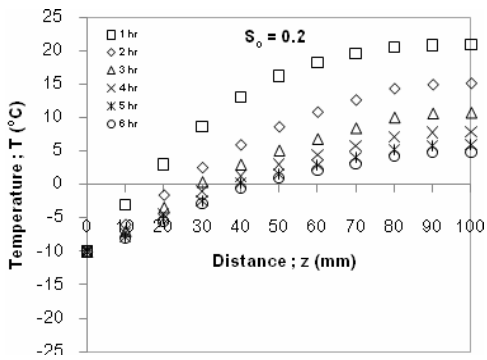
$$\varepsilon = \frac{V_v}{V_T} \qquad \textbf{(2)}$$

where V_v is the volume of void space and V_T is the total volume of packed bed, including the solid and void components. Porosity is a fraction between 0 and 1

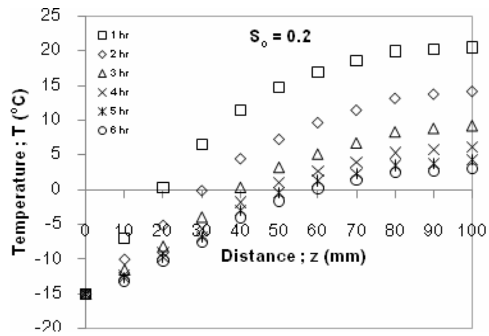
During the experimental freezing process, the uncertainty of our data might come from the variations in humidity and human errors. The uncertainty in freezing process is assumed to result from errors in the measured weight of the sample. The uncertainly in temperature is assumed to result from errors in measured temperature.

3. Results and discussion

The experiment data for freezing process in the unsaturated porous media are shown and are discussed as below.

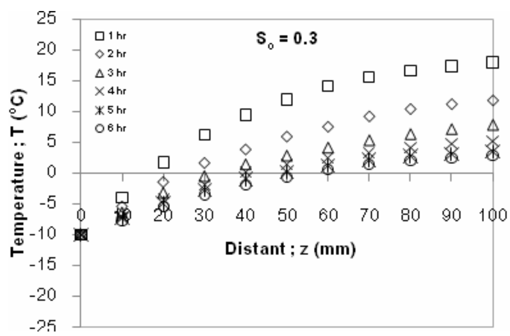


a) T_f = -10 ^oC and S_o = 0.2

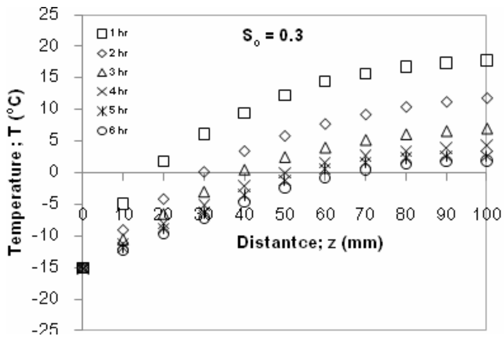


b) T_f = -15 ^oC and S_o = 0.2

Fig. 3 Temperature distribution inside packed bed at various times for case of S_o = 0.2 and different freezing temperature.

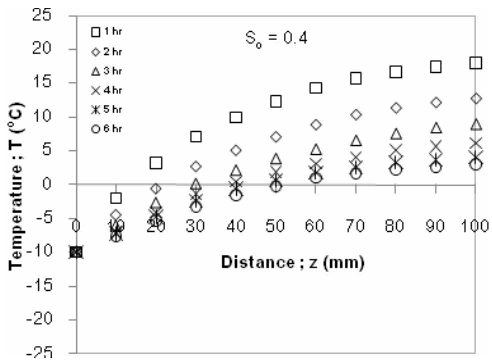


a) T_f = -10 ^oC and S_o = 0.3

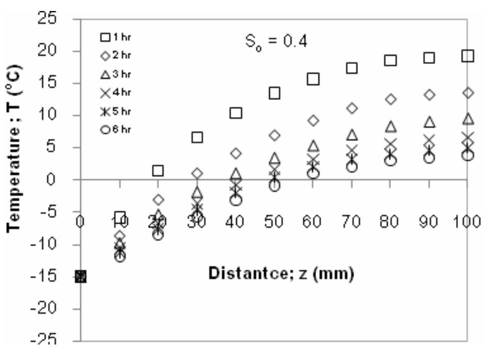


b) T_f = -15 ^{o}C and S_o = 0.3

Fig. 4 Temperature distribution inside packed bed at various times for case of S_o = 0.3 and different freezing temperature.



a) T_f = -10 ^{o}C and S_o = 0.4



b) T_f = -15 ^{o}C and S_o = 0.4

Fig. 5 Temperature distribution inside packed bed at various times for case of S_o = 0.4 and different freezing temperature.

Figures 3-5 show the temperature profiles in the packed bed for different initial water saturation and different freezing temperature. At every time, it is clarified that the temperature distribution in frozen zone is increased until equal to fusion temperature after that lead to the unfrozen zone, which temperature is higher than the fusion temperature. When, increased time the temperature gradient and the rate of freezing front is increased. In contrast at later time the temperature gradient is decreased and the rate of freezing front is slowly increased, Because frozen layer increases, the rate of solidification decreased due to the increasing thermal resistance to heat flow.

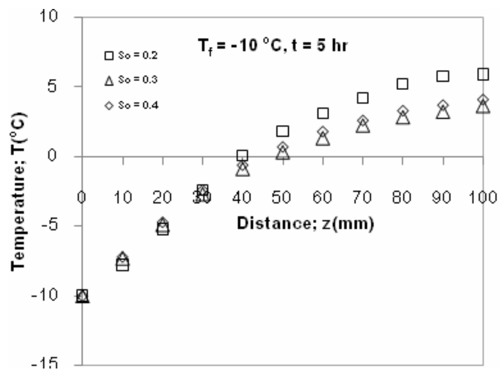
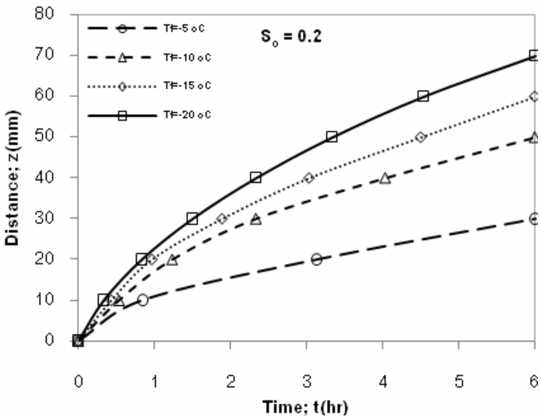
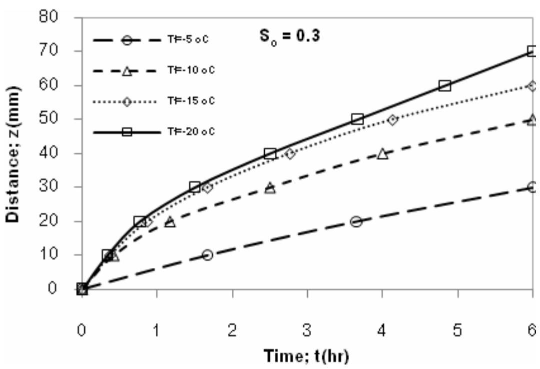


Fig. 6 Comparison of the temperature distribution for the cases of different initial saturation at t = 5 hr and T_f = -10 ^{o}C

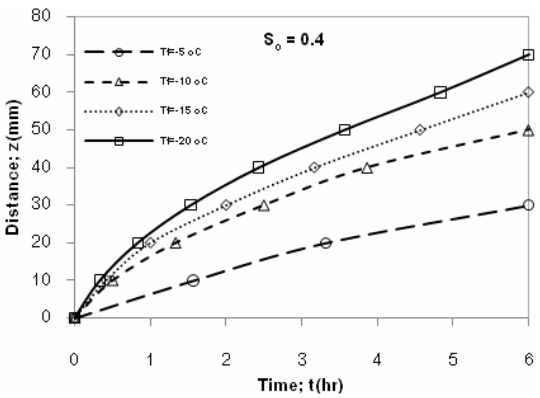
Figure 6 shows the temperature distribution inside packed bed for the cases of different initial saturation with t = 5 hr and T_f = -10 ^{o}C. It is observed that the temperature in the test cell drop faster in the case of high initial saturation compared with the case of low initial saturation. This is because the thermal conductivity in frozen layer becomes higher in the former case as a result of higher ice saturation.



a) $S_o = 0.2$



b) $S_o = 0.3$



c) $S_o = 0.4$

Fig. 7 Variation of the freezing front with time for case of different freezing temperature

Figures 7 show the Variation of the freezing front with time at different freezing temperature for the case of various initial saturation. It is observed that the frozen layer thickness is increasing rapidly in the early stages of the freezing process, but after that it becomes slowly increased. Furthermore, thickness of the case $S_o = 0.4$ is thicker compared with that of $S_o = 0.2$. These results may be explained by considering the latent heat of freezing and thermal conductivity in the frozen layer. Finally, it is found that the highest rate of freezing front corresponds to the lowest freezing temperature.

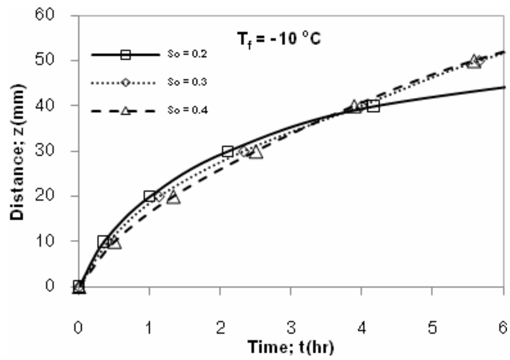
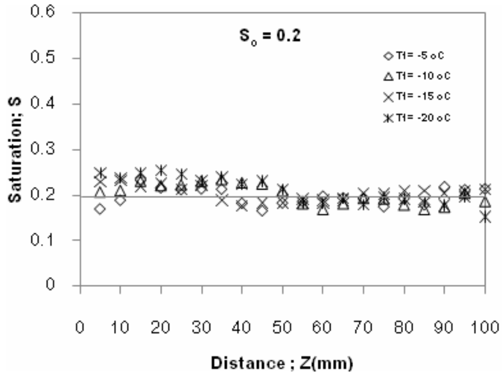
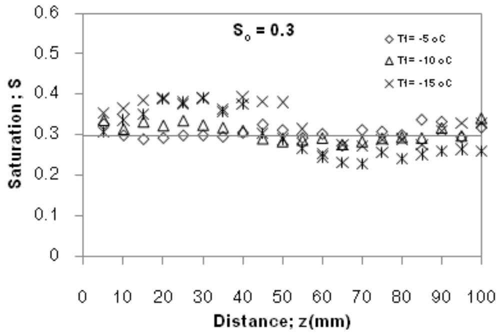


Fig. 8 Comparison of the freezing front for the cases of $S_o = 0.2$, $S_o = 0.3$ and $S_o = 0.4$

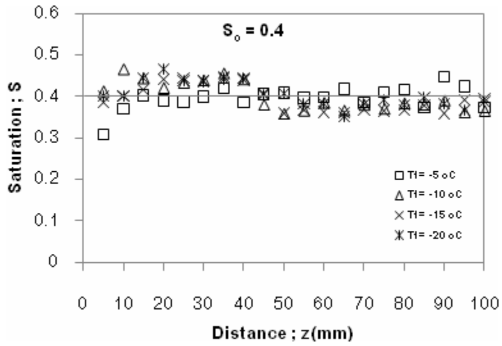
Figure 8 shows the time variation of the frozen layer thickness for the case of $S_o = 0.2$, $S_o = 0.3$ and $S_o = 0.4$ with $T_f = -10\ ^{o}C$. It is observed that the thickness of the case of $S_o = 0.3$ and $S_o = 0.4$ becomes thinner in the early stages of the freezing process, but after that it becomes thicker compared with that of $S_o = 0.2$. These results may be explained by considering the latent heat of freezing and thermal conductivity in the frozen layer.



a) S_o= 0.2



b) S_o= 0.3



c) S_o= 0.4

Fig. 9 Saturation distribution of ice and water at different freezing temperature and initial saturation.

Figures 9 show distribution of ice and water saturations during the solidification process in an unsaturated porous media at various condition. It is observed that the profiles are nonuniform, that is, ice saturation increase while water saturation is decreasing as compared with the initial state. This means the water in the unfrozen layer is absorbed to the solidification interface or freezing front during the solidification process due to capillary pressure[16]. Plays an important role more than gravity force. In addition, It is found that the water saturation in frozen layer for the case of is the S_o = 0.3 higher than case of S_o = 0.2 and 0.4, respectively. The rate of the absorption of water is increasing with increasing the freezing temperature. This is because the higher freezing temperature leads to a faster change of porous structure due to solidification, that is, it leads to a larger water saturation difference at the interface between the frozen and unfrozen layers to keep the same capillary pressure. Also, the rate of the absorption of water depends on water saturation at the interface; however, the relationship is more complex.

4. Conclusions

The freezing process in an unsaturated porous media considering heat and mass transport across moving boundary has been investigated experimentally. The unsaturated porous media are composed of glass beads, water and air pocket. The influences of the initial water saturation and constant temperature heat source on heat transfer and water transport across moving boundary during freezing process in unsaturated porous media are clarified in details. It is found that the rate of the absorption of water into the frozen layer depends on the freezing temperature and the water saturation at the freezing front. As a result, ice content in the frozen layer is related to the rate of water absorption and the freezing temperature. The results presented here provide a fundamental understanding of freezing process in porous media.

5. Acknowledgement

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