Review

"Heat and mass transfer in freezing porous media"

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Heat and mass transfer processes in porous media under phase transition conditions have a great scientific and practical interest in solving many engineering and technical problems. In this connection, several important examples are used: food preservation by freezing technology; cryopreservation and cryosurgery; permafrost of natural soil in harsh-climate regions such as Canada, the United States and North-East Asia; thawing and refreezing of soil around buried pipe lines, etc. Therefore the development of the models describing these processes with sufficient accuracy is very important.

The analysis of scientific and engineering literature in the considered area shows that the numbers of books involving these directions of study is very restricted.

In the applied part of the book presented, the author considers the important problems of geocryological direction, in particular the heat and moisture transfer in freezing soils (including permafrost). It is necessary to note the other books in this area (see for example, the last book: Edward Ershov and Edited by Peter J. Williams (2004). General Geocryology. Cambridge University Press), which considers the general principles of heat and moisture transfer on the basis of experimental analysis.

This book by Leonid Bronfenbrener couples the development of physical and mathematical models for heat and mass transfer processes in the freezing of porous media with utilizing them for the solution of practical geocryological problems. The solutions of the problems are obtained in dimensionless variables and criteria, characterizing the physical process that enable the author to compare the results for different values of the criteria. It should also be noted that all results of modeling represented in this book have an appropriate mathematical justification and are illustrated by comparison with experimental data. In this connection, detailed analysis of the results, their estimations and recommendations for the applications are described. The engineering approaches to the solutions of practical problems are also considered. In addition, on the basis of "Likeness and Dimensionalities Theory," the principles for the treatment of experimental data are formulated. This gives the author the possibility to generalize the experimental results and to obtain the functional relations of the main regularities (see sections 1.5 and 6.1). The new approaches to the modeling and, respectively, new physical and engineering results, reflecting the significant sides of the physical processes, are obtained and discussed in detail in this book.

The logical structure of the book, with clear theoretical exposition and physical interpretation of the results makes it comfortable for reading and using for practical work. The modeling heat and mass (moisture) transfer processes in heterogeneous porous media under phase transition conditions is considered from a unified point of view and, in contrast to the classical statement, the solutions of the problems are based on the three-zones models. The author assumes the existence of the region (freezing zone) of intensive phase transition, in which migration and crystallization of moisture take place simultaneously. It is known from experimental investigations that this region is characterized by sharp gradients of the equilibrium unfrozen water content, and its width depends on the soil properties and freezing conditions. In this connection, the analytical criterion for freezing zone formation has been derived by author as a function of soil properties and freezing conditions. This new result, a priori, enables the correct choice of the problem solution, i. e. whether to consider the phase front by allowing the presence of a freezing zone – three-zone model, or to consider the phase change interface as a boundary which divides the soil region to frozen and unfrozen zones – two-zone model (classical statement of the problem).

Another important aspect of the problem should be noted. In the scientific literature, the relaxation analysis of the phase transitions in fine-grained porous media is absent or considered on the level of general description. Nevertheless, as is shown in the book, just the relaxation terms ($\partial I/\partial t$, where I and t are ice content and time, respectively) in the system of equations allows the introduction into the model of the crystallization rate function – non-instantaneous kinetics and, consequently, to determine the ice distributions in both the frozen and the freezing zones. This very important aspect is described in detail. For this purpose, on the basis of the general balances of heat and mass transfer for the multiphase systems (soil-water-ice), the author derived the system of equations for the phase transitions processes with relaxation terms (Chapter 1).

In this connection, the approaches and solutions in both the relaxation model of freezing and non-instantaneous kinetic model should be noted (Chapter 3). These models are based on the "three-zone model" and allow calculating the ice content distribution and thereby distribution of total moisture content – one from the very important characteristic of freezing and frozen soils used in engineering applications (analysis and design).

The new experimental express-method for determination of the time of water crystallization in porous media – the essential characteristic for the kinetic model, is presented. In this respect, the advance theoretical substantiation and form for the treatment of the experimental data is derived and discussed (section 1.5). At the same time, based on the treatment of experimental data on the equilibrium unfrozen water content (including experimental results by the author) by the linear regression method, the analytical function of this very important value is obtained in dimensionless variables (Chapter 2). This function is applied in the models presented in this book.

A new and original approach is proposed for the solution of the problem on secondary frost heave (Chapter 7). The author suggests using within kinetic zone (frozen fringe) the distribution of the moisture by approximation of the experimental data for the equilibrium unfrozen water content instead of generalization of the Clapeyron relation which is used in the works. This distribution is the result of the complicated interaction between water, ice and the mineral skeleton during the freezing process and is controlled by the external (given) temperature gradient. The generalization of the Clapeyron relation estimates only the drop of the initial freezing temperature in porous medium and is not connected with the external temperature gradient, which is responsible for the frost heave process. The detailed discussion of this very important physical aspect is presented in the book. In this connection, the new results, related to the frost heave distribution and its rate, are considered. Also obtained and discussed in detail are a number of new results, concerning Miller's and Gilpin's models for thermo regilation process. The comparison between calculations results which are obtained according to both models is also discussed. It is important that the results for the frost heave and frost penetration obtained by theoretical calculations are in agreement with results obtained by numerical methods and in experimental investigations (see Figs. 7.10 and 7.14). This allows applying the model for prediction and analysis of this phenomenon in the solution of practical problems (design and construction in cold regions).

In Chapter 4, based on the system of equations including the non-instantaneous kinetic model for crystallization, the general model of the freezing process in the soil is considered. The solution of this complicated problem is obtained by a numerical method. As is needed for numerical methods, the author gives the analysis of both the stability of finite-difference scheme and convergence of the iteration process. It is observed a good agreement of the results obtained by numerical solution and in experimental investigations. At the same time, an important and interesting result was obtained. According to the distributions, self-sustained oscillations of the heat and moisture fluxes and also the phase front propagation have been obtained. This result reflects the loss by phase front of monotonous movement (dynamic instability) and results in segregate texture formation (Fig.4.7).

The stability of the phase front is considered in Chapters 5 and 8. As a new result for the freezing of porous media, the analytical criteria of the phase front stability (formulae 5.30 and 8.48) are derived. These criteria are obtained for the freezing process, in which the frost heave is not observed and also of its occurrence. It is very important that these criteria take into consideration the non-instantaneous crystallization process in the kinetic zone, and that the rate of crystallization is a function of supercooling. According to the "Likeness and Dimensionalities Theory," the stability criteria depend upon the Stefan, Lewis and Peclet numbers, on the parameter, describing the non-instantaneous kinetics of phase transitions, and also on the dimensionless parameters characterizing the frost heave process. By Fourier synthesis, the actual front shape evolution is calculated. A new physical result is obtained. According to this result, the scale of periodic morphology of the front structure is significantly unrelated to that of the initial (starting) perturbation. The effect of the non-instantaneous kinetics on the front shape evolution is described. It is necessary to note that the stability/instability state of the phase front has a significant effect on the cryogenic structure of soil. In this book, the engineering aspect is considered in detail (sections 5.3 and 8.4).

The results of the field experiments carried out by the author are presented in Chapter 6. The treatment of the experimental results has been done according to the “Likeness and Dimensionalities Theory”. In this chapter, the author describes the soils properties (loamy and sandy soils) of the regions and temperature behavior of permafrost. Based on the dimensionalities analysis the dimensionless form for the treatment of the experimental results by dimensionless variables and criteria was obtained. By method of linear regression, the temperature distributions and phase front propagation are presented (Figs. 6.1-6.3) for considered types of soils. The analysis of theoretical results and their comparison with experimental distributions allows applying the principles and functional dependences in the practical problems for prediction of the significant components of freezing and thawing soils in cold regions. It is also given the numerical solution of the appropriate boundary value problem and comparison between calculation and experimental results.

In this book, the general solution for the very important practical (technological) problem: the thawing and refreezing of the frozen soil (permafrost) around a hot buried pipeline is also presented. In this context, by conformal mapping, the general solution of the problem is obtained. Moreover, on the basis of the general solution and correlation analysis, the simple dependence of the fluid temperature versus time in refreezing process was derived (formula 6.59). Also obtained is one of the very important characteristics for the design and laying of the pipelines in cold regions – the time required for hot fluid (oil or other fluid) to cool up to a specified temperature during the refreezing of soil, when the transport of fluid is stopped (formula 6.61).

In the course of the discussions with the author, a number of comments and suggestions were made which have been taken into consideration for the revised manuscript of the book. In particular, according to my comments, the revised version added the verification of the relaxation model of freezing. For this reason the comparison of the calculation results obtained from modeling with results of experimental investigations and appropriate explanations was described (p. 140-141; Fig. 3.5 of the book manuscript). For the non-instantaneous kinetic model, a more complete description of the physical prerequisite for the quasi-heterogeneous scheme was added as well as an estimation of the interval of the local phase transition (p. 154 of the book manuscript). The detailed derivation of the equations (6.54) and (6.55) – transformation of the phase front location from the bipolar coordinate to the Cartesian system and also time transformation, is presented in Appendix 6A.

In conclusion, I would like to note the following: The composition of new approaches and methods for the solution of the heat and moisture transfer processes in porous media under phase transition conditions, and their modeling with applications of the results to the practical problems make this book interesting and important for both scientific researchers in area of heat and mass transfer in porous media and applied engineering specialists working in research, design and construction in cold regions. This book can be also useful for the students and PhD students specializing in thermal physics of phase transitions, Geocryology and appropriate applied scientific fields.

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