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Heat and mass transfer in melting porous media: Stable miscible displacements

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ABSTRACT

Changes in the porosity and permeability of a porous medium due to melting are modeled. A frozen phase, which initially fills a part of the porous medium, melts and gets dissolved in the injected hot solvent. The amount of melted material, the rate of melting as well as the profiles of temperature, porosity, and concentration are analyzed to understand the nature of this naturally and industrially important phenomenon. Four reference scenarios corresponding to instantaneous thermal equilibrium, no heat transfer to the frozen phase, no-melting, and instantaneous melting conditions are solved analytically and the effects of different parameters are discussed. Numerical simulation results show that the profiles of the fluid temperature, porosity of the medium, and solvent concentration, form three fronts moving at different rates. It is found that for heat transfer coefficients above a certain value, the rate of melting is independent of this parameter and the system can be considered to have reached instantaneous thermal equilibrium. Moreover, slow heat transfer in the medium is shown to increase the rate of melting at long time periods by involving larger areas in the melting process. Heterogeneous scenarios are also analyzed by introducing frozen blocks of different geometries. The ability of the flow to bypass the frozen region involves a new heat transfer mechanism identified as outer-boundary convection. The effects of the geometry of the block along with the other parameters on the melting process are examined. Furthermore a generalizing scheme is proposed to predict the melt production for different block geometries and values of the saturation of the frozen phase.

1. Introduction

The structure of a porous medium may change dynamically by fluid flow, as a result of heat and mass transfer. In this study, miscible displacement processes in media with changing porosity due to melting are investigated. Such interactions can be encountered in a number of natural phenomena such as the flow of magma, melting of sea ice or frozen soil as well as in industrial processes such as secondary oil recovery or solute transport processes. In these processes the frozen region is porous and has some permeability to the heated fluid. Therefore the convection of heat through the frozen region is one of the main mechanisms of heat transfer in such systems. In this regard this model is different from the classical works studying the melting of frozen porous media [1–3] or the melting cavities [4,5] in which conduction and natural convection are responsible for the heat transfer to the boundaries of the frozen region.

As stated earlier, there are many fields in which melting in the porous medium is central to the flow. These include the flow of magma melting the rocks and the ensuing change in the permeability of the medium which has been the subject of numerous studies [6–8]. The porous medium in which the magma flows is considered to be deformable and heat and mass transfer occur through the melting of the rocks and chemical reactions between the components of the magma and the solid phase [7]. The heat transfer equations describing these models are the closest to our model since they include the effect of the convection of the hot fluid through the melting porous medium. The deformable porous medium of such systems is replaced in our model by a melting solid phase and a non-deformable rock phase.

Melting of ice due to the flow of water in partially frozen soil is another related application. Studies on such systems started in the 1920s with the attempts to model heat and fluid transport in frozen soil and to address frost related damage of roads in Scandinavia and North America [9–12]. Uneven ground displacements due to heaving pressure, loss of mechanical strength of the soil due to thawing of the ice in the frozen regions, and changes in unfrozen water level beneath the permafrost are examples of problems investigated through such modelings. Despite some similarities between the present study and those discussing freezing

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and thawing of frozen ground, the models and the relevant concepts are different. The driving forces for the flow in frozen soils consist of gravity and the increase in the volume of water upon freezing which pushes the moisture towards the colder regions and causes the flow of heat and mass in the medium [9]. Furthermore, the models describing freezing and thawing of the ground are configured mostly in one dimension along the gravity direction [9,10]. In the present study however, changes in the specific volume upon melting as well as the effects of gravity are neglected while the flow is induced by the injection of the solvent to the medium.

Changes in the medium porosity are also encountered in the field of oil recovery, which is the main motivation of the present study. This pertains in particular to the hot solvent flooding of preheated bitumen reservoirs where the inhabitant fluid is immobile and may be regarded as frozen at the initial temperature. In the recovery of bitumen or heavy oil, the co-injection of a solvent with a heating medium (mostly steam) has become popular and many studies have been devoted in recent years to processes like solvent aided SAGD, VAPEX and solvent assisted hot water flooding [13–15]. Melting of the bitumen occupying some of the pore space of the medium changes the porosity available to the fluids and in turn the dynamics of the flow. The formation of the melting zone through injection of hot solvent to the bitumen reservoirs has not been studied before.

Our objective of this work is to understand the effect of parameters such as the initial porosity, the rate of heat transfer and the melting potential of the flowing fluid on the melting rate and the development of the melting zone. Such a systematic study of the melting process is beneficial in describing and predicting the trends of natural phenomena such as melting of sea ice and thawing of soil. Also a better understanding of the trends of heat and solvent transfer to the bitumen at different conditions can help enhance the efficiency and reduce the environmental impacts of these industrial processes.

A detailed definition of the problem, along with the mathematical and numerical models are presented in the next section. In the Results section, at first four reference scenarios are defined for the melting process according to which different scenarios can be categorized. Then a quantitative study is presented which aims at predicting the melting rate as a function of the flow conditions and determining the conditions that lead to the maximum melting. At last the melting mechanisms in heterogeneous media are discussed and a quantitative analysis of the process is carried for different configurations of the frozen region.

2. Modeling

The problem is defined such that the porous medium is partially saturated with a frozen material. The rest of the porous medium is filled with a fluid (e.g. the melt) that is fully miscible with the melted form of the frozen phase. A hot fluid, fully miscible with the inhabitant one, is injected in the medium to displace the inhabitant fluid and the melt. Due to the heat of the injected fluid, the frozen material is melted and the pore space it initially occupied becomes available to the flow. To model this system, it is assumed that three phases are present in the medium, namely the rock or the porous medium, the frozen fluid or the solid phase and the fluid or the flowing phase. The rock in this model is the part of the solid matrix that remains unchanged during the whole displacement process and has a *homogeneous* porosity distribution of ϕ_R. In other words, the void space per unit volume available to the flow if no frozen material is present is ϕ_R. The porous medium is partially saturated with the frozen material, or what we refer to as the solid phase, of volume per unit volume of formation $(\phi_R - \phi)$, where $\phi = \phi(x, y, t)$ is the porosity available to the fluid flow in the presence of the frozen phase. The porosity $\phi(x, y, t)$ changes dynamically with the variation of the saturation of the frozen material in the medium.

When the thermal front floods a region, it melts part of the frozen material in the area it comes in contact with and increases its porosity and permeability. Initially the saturation of the frozen material in the frozen medium is at its maximum value S_0 providing a minimum pore space for the flow, referred to as ϕ_{min}. In any displacement scenario, the porosity can vary between the initial porosity ϕ_{min} and the rock porosity ϕ_R. Fig. 1 shows a schematic of the melting process. At the initial stage (Fig. 1a) the medium has a porosity ϕ_{min} and all three phases are at thermal equilibrium at the melting temperature T_m. When the heated fluid is injected into the medium (Fig. 1b) there is a difference between the temperatures of the frozen material and the flowing fluid which provides a source of heat for melting. As a result of the gradual melting of the remainders of the frozen material in the medium, the porosity increases and ultimately reaches that of the rock, ϕ_R.

At the scale of the reservoir, the model is defined as a hot solvent with concentration C_1 and temperature T_1 being injected at a uniform rate U into a rectangular porous domain of length L and width W and initial porosity ϕ_{min} (see Fig. 2). The injected fluid displaces the inhabitant one, of concentration C_2 and temperature T_m as well as the melted material, and heats the medium. The concentration, temperature and porosity form advancing fronts that

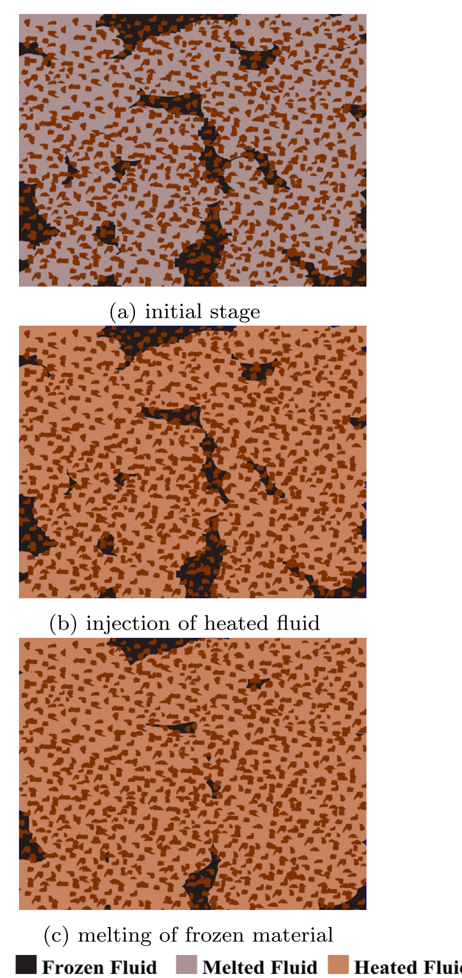

Fig. 1. Schematic of the phases present in the domain and the melting process: (a) initial stage with rock, frozen material, and melted fluid present; (b) volume flooded by heated fluid; (c) melting of the remainders of frozen material.