Non-thermal equilibrium two-phase flow for melt migration and ascent

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We develop a theory for heat exchange between a fluid phase in a solid porous matrix where the temperature of the fluid and of the matrix are different, i. e. not in thermal equilibrium. The formulation considers moving of the fluid within the porous matrix as well as moving of the matrix in an Eulerian grid. The theory can be applied to melts in partially molten rocks, particularly aiming at the transitional regime between melt percolation and flow through dikes, as well as to brine transport in porous rocks.

The theory involves the energy conservation equations for the fluid and the solid phase which are coupled by a heat exchange term. We derive an expression based on a Fourier decomposition of a periodic half-waves for a macroscopic description of the non-equal temperatures in the fluid and the solid considering the relative volumetric fractions and surface to volume relations of the pores. We present a formulation for the heat exchange between the two phases taking into account different thermal conductivities of the fluid and the solid and considering the temporal evolution of the heat exchange. The latter leads to a convolution integral in case of a resting matrix. The evolution of the temperature in both phases with time is derived upon inserting the heat exchange term in the energy equations.

We test the theory for a simple 1D case of sudden temperature difference between fluid and solid and vary fluid fractions and differential velocities between fluid and solid to obtain the requisites for the maximum Fourier coefficient and the time increments for numerical integration. The necessary time increments are small (between $10^{-3}d^2/\kappa$ to $10^{-5}d^2/\kappa$, where d is a scaling length, e.g. the pore radius and κ is a scaling diffusivity, e.g. the mean diffusivity) and strongly depend on the fluid fraction. The maximum Fourier coefficient need to be as high as 500 to resolve properly the sudden heat exchange between fluid and solid. Our results agree well with an analytical solution for non-moving fluid and solid and support an approximative solution by Minkowycz et al. (1999). The temperature difference between solid and fluid depend on the Peclet number (i. e. the velocity difference between fluid and solid). For Peclet numbers up to 100, the temperature difference after one diffusion time is as large as $0.15\ T$ (where T is a scaling temperature). Thus, our results imply that thermal non-equilibrium can play an important role in melt migration once the melt has focused into channels which is associated with a significant increase in the Peclet number, and may affect the distance of how deep melt may penetrate into macroscopically sub-solidus regions.