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Surfaces of hyperbolic-parabolic transition in the problem of flow with variable number of phases through porous media

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An interface of phase transition is a macroscopic surface that separates the domain occupied by a single-phase gas or liquid from another domain occupied by two-phase gas-liquid mixture. In classical fluid dynamics an example of such a surface is the boundary of a cloud or a spray in the air. In porous media, this corresponds to the injection of miscible gas in an oil reservoir, which creates the zone of single-phase gas near the injection well, another zone of single-phase oil near the producing well, and a two-phase zone between them. Two mobile boundaries of the two-phase zone are the surfaces of phase transition. To model such systems, the method of negative saturations has been developed, which enables us to describe the overall fluid in all zones by a uniform system of extended two-phase equations and to solve it by direct numerical simulation without applying any special technique of front tracking. In this method the overall fluid is assumed to be pseudo two-phase. The extended system of equations is obtained from the principle of equivalence between the two-phase and single-phase flow.

Such an extended model of two-phase flow can be reduced to a single equation of nonlinear kinematic waves with respect to the gas saturation. It contains some non-classical terms like the extra-diffusion (the diffusion of phase saturation). This equation is parabolic in the subdomains that correspond to the true single-phase fluid, and hyperbolic in the zone of the true two-phase flow. Then a physical surface of phase transition is equivalent to the mathematical interface of transition between hyperbolicity and parabolicity (HP-transition). It is possible to show that such an interface represents a strong discontinuity of the solution (HP-shocks). We develop the extended Hugoniot-Rankine conditions and the entropy conditions for them. For one-dimensional Riemann problem, a graphical technique has been developed, which enables us to calculate the exact velocity of a HP-shock and the saturation behind and ahead of it. For numerical simulation of the extended two-phase model with HP-transition, two types of regularization are analysed: the introduction of small capillary or fictitious diffusion and the Kirchhoff regularization. Several examples of the solution are shown.

References

M. Panfilov. Physicochemical Fluid Dynamics of Porous Media. Wiley & Sons, 2018 (in edition)

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