Use of Computed X-Ray Tomographic Data for Analyzing the Thermodynamics of a Dissociating Porous Sand/Hydrate Mixture

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X-ray computed tomography (CT) is a method that has been used extensively in laboratory experiments for measuring rock properties and fluid transport behavior. More recently, CT scanning has been applied successfully to detect the presence and study the behavior of naturally occurring hydrates. In this study, we used a modified medical CT scanner to image and analyze the progression of a dissociation front in a synthetic methane hydrate/sand mixture. The sample was initially scanned under conditions at which the hydrate is stable (atmospheric pressure and liquid nitrogen temperature, 77 K). The end of the sample holder was then exposed to the ambient air, and the core was continuously scanned as dissociation occurred in response to the rising temperature. CT imaging captured the advancing dissociation front clearly and accurately. The evolved gas volume was monitored as a function of time. Measured by CT, the advancing hydrate dissociation front was modeled as a thermal conduction problem explicitly incorporating the enthalpy of dissociation, using the Stefan moving-boundary-value approach. The assumptions needed to perform the analysis consisted of temperatures at the model boundaries. The estimated value for thermal conductivity of 2.6 W/m K for the remaining water ice/sand mixture is higher than expected based on conduction alone; this high value may represent a lumped parameter that incorporates the processes of heat conduction, methane gas convection, and any kinetic effects that occur during dissociation. The technique presented here has broad implications for future laboratory and field testing that incorporates geophysical techniques to monitor gas hydrate dissociation.

Introduction

X-ray computed tomography (CT) has been applied by various researchers to visualize methane hydrates (Uchida, 2000, Mikami, 2000). Recently, Tomutsa et al. (2002) have shown that CT can be used to track (temporally and spatially) the progression of a dissociation front in a hydrate/sand sample. The objective of this paper is to demonstrate the use of CT, along with simple thermodynamic assumptions, to estimate the thermal conductivity that accompanies the complex mass and heat transfer processes associated with hydrate dissociation in a hydrate/sand system. Properties of pure methane hydrate have been studied in the laboratory, and the basic thermodynamic properties, including phase stability, heat capacity, and thermal conductivity, have been quantified over a significant range of temperatures and pressures (Sloan, 1998). However, extrapolating thermodynamic properties to methane hydrate within a natural porous formation remains a formidable challenge. Theoretical models for mixed systems abound, but actual data for hydrate/sand systems are very sparse. Estimates of the bulk heat capacity may be obtained by summing the heat-capacity contributions from the individual phases as long as such estimates suitably incorporate the strong dependence of heat capacity on temperature. Thermal conductivity, however, is dependent not just upon the intrinsic conductivity of the individual phases, but also a function of the thermal resistances across grain contacts, properties that depend on the quality, areas and geometry of such contacts. When complex processes such as hydrate dissociation and advective transport occur, estimating heat transport properties and the migration rates of phase boundaries is challenging and the required data and insight for modeling is lacking.

This paper uses a moving-boundary-value model, attributed to J. Stefan for his work on modeling melting of polar ice caps and icebergs in the 1890s. Here we apply a moving-boundary-model to interpret acquired CT data that tracks the time-dependent progression of a dissociation front in a cylindrical sand/hydrate sample. Only simple assumptions of constant boundary temperatures are required to apply the model. Previous researchers (Selim and Sloan, 1985, Ahmadi et al., 2000, and Tsypkin, 2000) have suggested the applicability of the moving-boundary-value problem to model hydrate dissociation, but have not provided any actual data. The ability for CT to track the time dependent progression of the hydrate dissociation front has provided an opportunity for direct application of a moving-boundary-value simulation. Although the model explicitly accounts for heat conduction with phase

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