International Journal of Rock Mechanics and Mining Sciences 108 (2018) 15–22

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Technique of rock thermal conductivity evaluation on core cuttings and non-consolidated rocks

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ARTICLE INFO

Keywords:
Thermal conductivity
Rock cuttings
Inverse problem
Homogenization
Experiment

ABSTRACT

The paper focuses on the development of a new technique to evaluate thermal conductivity of rock core cuttings and non-consolidated rocks. Very often consolidated cores cannot be recovered even during the well drilling in high porous and/or fractured reservoirs. At the same time reliable data on rock thermal properties are required for basin and petroleum system modeling, hydrodynamic modeling of hydrocarbon producing with thermal methods of enhanced oil recovery, interpretation of temperature logging data, heat flow density determination, etc. The proposed methodology is based on preparation of the synthetic composite specimens consisting of rock particles mixed with material-fillers (wax, water, air), measurements of the thermal conductivity of these specimens and evaluation of the thermal properties of the particles solving inverse problem of homogenization. The thermal conductivity is measured using the optical scanning technique which is a rapid, non-destructive, contactless methodology providing high accuracy (providing evaluation of thermal conductivity with uncertainty not more than ± 6% at confidence level of 0.95). The results of measurements are used as the effective properties in various homogenization schemes to evaluate properties of the inhomogeneities. To validate the approach, we calculated effective thermal properties using Mori-Tanaka-Benveniste and Maxwell micromechanical schemes and compared analytical predictions against experimental data. Our results show a good correspondence between micromechanical approximations and experimental measurements with average absolute error no more than 4%. Inverse homogenization problem was formulated to reconstruct thermal properties of considered rock cuttings from the known properties of remaining constituents and measured effective properties. Approximations based on inverse Mori-Tanaka-Beneveniste and Maxwell schemes are compared against experimental data measured on solid rock specimens. Satisfactory agreement between inverse solutions and experimental data were observed for both MTB and Mawell schemes with with average absolute error no more than 6%. The sensitivity analysis of the results to the shape of inhomogeneities corresponding to the entrapped air was performed.

1. Introduction

Presently, the representative data on the rock thermal properties can be obtained mainly from the measurements on consolidated cores since there are no reliable wire-line well logging techniques for rock thermal property measurements in-situ[1,2] and existing techniques for the rock thermal property on core cuttings[3–5] may be not satisfactory for practical application. It is a serious problem, in particular, for oil-gas exploration science and industry since, in most cases, wells are drilled with recovery of rock cuttings and nonconsolidated rocks rather than consolidated core. Very often consolidated cores can not be recovered even during the well drilling in high porous and/or fractured reservoirs. At the same time reliable data on rock thermal properties are required for basin and petroleum system modeling,[6] hydrodynamic modeling of hydrocarbon producing with thermal methods of enhanced oil recovery,[7] interpretation of temperature logging data,[8] heat flow density determination[4,8] etc. It was established recently that detailed data on the rock thermal conductivity provide important data on geological structure of formations.[9] Approaches have recently been developed to use the rock thermal conductivity data to evaluate content of total organic carbon, sonic velocities, density, mechanical properties, natural radioactivity and variations in mineralogical composition for

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https://doi.org/10.1016/j.ijrmms.2018.05.005
Received 21 December 2017; Received in revised form 28 April 2018; Accepted 7 May 2018
1365-1609/

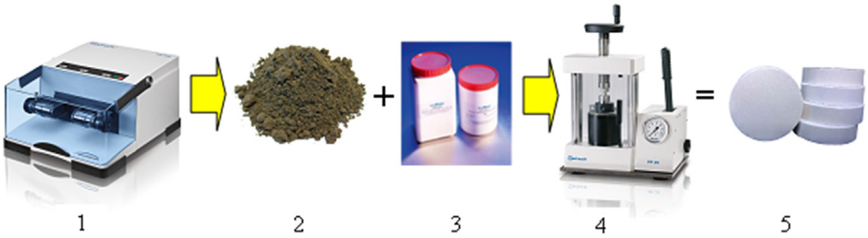

Fig. 1. The ball mill (1) and press machine (4) for preparation of synthetic specimens (5) as mixture of rock cuttings (2) and wax-filler (3).

conventional and unconventional hydrocarbon reservoirs.[10,11]

The approach for the rock cuttings thermal conductivity measurements was suggested and used earlier when core cuttings (with possible thermal conductivity ranging from 1.5 to 6 W/(m K)) were mixed with water (thermal conductivity of ~0.60 W/(m K)) and the line source technique was used to measure the mixture thermal conductivity.[4,5] However, it requires too big volume of core cuttings (about 100 ml) and can not provide the fast numerous measurements.[5] Theoretical Lichtenecker's model[12,13] of effective thermal conductivity (the geometric mean mixing law) is used in this approach although it was shown that the model gives essential uncertainties for two component medium if contrast in thermal conductivity of two components exceeds 20:1.[3] Duration of the effective thermal conductivity measurement with the line source technique is too long (about 15 min) for numerous measurements on many rock cuttings portions. Hundreds of the measurements for every well are required usually in practical geophysics to obtain representative experimental data on detailed variations of rock thermal conductivity along wells to provide comprehensive information for different application of rock thermal conductivity for exploration, prospecting and development of hydrocarbon fields.

We propose an approach to the rock cuttings thermal conductivity evaluation. This approach provides (1) mixing small portion of rock cuttings (not more than 20 g) with material-filler, (2) fast express preparation of solid synthetic specimens, (3) fast numerous high-precision measurements of effective thermal conductivity on synthetic specimens with advanced optical scanning technique,[2] (4) evaluation of rock cuttings thermal conductivity with uncertainty not more than ± 6% (at confidence level of 0.95). We suppose that grinded particles represent thermal properties of matrix of the original rock and can be considered as a single constituent in a mixture practically for any type of rocks.

The last step in the procedure involves solution of the inverse problem which can be formulated in two forms: (a) recovery of information on the microstructure of materials when effective properties and properties of the constituents are known and (b) evaluation of the material properties of one of the constituents when overall properties, microstructure and properties of the other constituents are known (microstructural information required for this process includes volume fraction of the inhomogeneities and information that can be obtained from microscopy analysis - their average shape and orientation). Extraction of the microstructural information from the effective properties has been a subject of substantial attention, in connection with various materials and various effective properties measured. In rock mechanics, the problem of interest is the recovery of information on crack systems from the effective moduli[14] and wave-speed data is often used in this context.[15] Monitoring of microstructure is an important problem in biomedical applications, for example, in connection with the evolution of microstructure of bones due to aging and other factors.[16] Several numerical algorithms of recovery of the microstructural information from measured transport properties of composite materials were suggested in.[17] The extraction of microstructural information from the effective properties involves uncertainties, due to an obvious non-uniqueness in this inverse problem.[18] The extent of uncertainty strongly depends on the type of the overall anisotropy; it is reduced if partial information on defect shapes or on the overall porosity becomes independently available.

In the present work, we discuss recovery of information on the thermal conductivity of inhomogeneities (milled rock cuttings) while overall thermal conductivity and morphology of the material are known.[33,34] The approach is based on the concept of conductivity/resistivity contribution tensors of the inhomogeneities. The technology is designed for integration into standard process of cutting investigation on site, that includes washing cuttings from the drilling fluid and subsequent drying. A small amount of mud particles remaining in the pores after drying does not greatly influence on the effective thermal conductivity.

2. Materials and methods

Our approach can be formulated as follows: (1) development of a stable technique for rapid synthetic specimens preparation, (2) adjustment of existing optical scanning method for the measurements of thermal properties of the synthetic specimens to provide high metrological quality, (3) development of theoretical models to estimate thermal conductivity of the rock, (4) metrological testing of the technology on the specimens with known properties.

We start with the development of a stable technology for synthetic specimen preparation that provides small uncertainties in effective thermal conductivity. The following experimental setup was used to prepare synthetic specimens (Fig. 1): (1) a special ball mill (Retsch company) to prepare rock cuttings that will be mixed with binder, (2) a press machine (Retsch company). To validate the methodology we used rock cuttings with known thermophysical properties. For this goal, big blocks of several types of rocks and technical glasses were used for synthetic specimens preparation. Rock specimens that are not essentially heterogeneous were prepared and studied for their thermal conductivity and its stability within the specimens using the optical scanning technique (Fig. 2). For glasses, we used officially certified thermal properties. The lamp version of the optical scanning instrument for measurements of the thermal properties of filling materials and synthetic specimens was utilized that provides accuracy and precision both of ± 1.5% with total uncertainty of ± 2.5% at confidence level of 0.95.[2]

In order to provide high metrological quality of experiments the influence of the following factors on stability of the technology was analyzed: (1) frequency of vibrations provided by mill machine during preparation of rock cuttings form rock and glasses, (2) duration of treatment of rock and glass blocks to prepare cuttings with satisfactory particle dimensions, (3) pressure in the press machine during preparation of the rock cuttings and binder mixture, (4) time of pressing during synthetic specimen preparation, (5) influence of binder material temperature to provide the best thermal contacts between specimen constituents and minimize volume fraction of air.

3. Preparation of the synthetic specimens with rock cuttings

More than 100 experiments with synthetic specimens preparation have been prepared to develop a stable technology. The most appropriate grinding regime for big pieces of consolidated marble and granite