Monitoring Imbibition and Estimating Residual Gas Saturation Using Low Field NMR*

Minghua Ding[1] and Apostolos Kantzas[1]

Search and Discovery Article #41599 (2015)
Posted March 20, 2015

*Adapted from extended abstract prepared in conjunction with a presentation given at CSPG/CSEG 2004 GeoConvention, Calgary, AB, Canada, May 31-June 4, 2004,

[1] Department of Chemical and Petroleum Engineering and TIPM Laboratory, University of Calgary, Calgary, AB, Canada (mding@ucalgary.ca)

Abstract

Residual gas saturation is known to be a key factor to determine gas recovery from gas reservoirs with water influx. The influx of water controls all important recovery mechanisms in these gas reservoirs. Water imbibition has long been recognized as an important factor in recovering gas from water-wet, fractured gas reservoirs subjected to water flood and water drive. In order to carefully study residual gas saturation due to water imbibition, both spontaneous and forced co-current imbibition tests were performed in a group of plugs from a Western-Canada sandstone reservoir and in Berea sandstone plugs. On-line NMR was used to monitor the in-situ gas saturation and the distribution of water in the pore space. Forced imbibition tests followed the spontaneous imbibition tests through a gradual increase of the water flow rate to evaluate the final residual gas saturation. The results indicate that the residual saturation depends not only on flow rates, but also on other parameters such as experimental time, reservoir properties, capillary number, etc. In this study, we present experimental results of the different imbibition processes, along with the corresponding capillary number analysis and the definitive criteria for mobilization of residual gas during horizontal displacements. The potential applicability of such criteria in gas reservoirs is discussed.

Introduction

Gas reservoirs with a naturally occurring underlying aquifer and aquifer gas storage are most common projects in gas reservoirs. Both caused large volumes of gas to be trapped and unrecovered. Once gas is trapped, it is very difficult to be remobilized from the porous media. To precisely evaluate residual gas saturation is very important to calculate the gas recovery and further develop the strategy of enhancing gas recovery. The experimental research work were presented in Kantzas et al. (2000), in which experiments were performed in both sandstone and carbonate reservoirs and residual gas saturation was evaluated. Some factors such as wettability, imbibition rate and experimental procedures, which affecting the residual gas saturation, were discussed. Crowell et al. (1966) discussed the efficiency of gas recovery by water imbibition. It was shown that gas recovery is a strong function of the initial gas saturation and that the maximum recovery is obtained at zero initial water saturation. The experiments were done with Berea sandstone cores. Similar results were obtained for Boise sandstone cores. Free imbibition or forced imbibition at a constant flow rate seemed to have no difference in terms of final recovery of gas in Boise sandstone. A slight increase in gas recovery with a reduction of interfacial tension was observed in Berea slabs. The changing of interfacial tension will lend a changing of capillary number.

Capillary number is defined as the ratio of viscous forces to capillary forces. Increasing capillary number has long been investigated as a strategy for improving oil recovery. Many methodologies either tested in laboratory or applied in the field involved increasing the capillary number. The pressure gradient required to move the trapped non-wetting phase through a capillary tube is much higher than what would be predicted by the pipe flow equation, due to the pressure discontinuity at the wetting/non-wetting interface. Due to the contact angle hysteresis, this discontinuity is not of the same magnitude on both sides of the trapped non-wetting phase. As an oil drop is pushed through a pore throat, its downstream end is squeezed into a much narrower segment, making its radius of curvature much smaller than the upstream part. The fraction of non-wetting phase that is trapped depends on the value of capillary number in the system. Experimental work also showed that once the non-wetting phase is trapped, remobilization through increasing the displacement velocity is not easy. Numerous papers have been written on the subject of trapped oil remobilization after increasing the capillary number, but fewer on the subject of remobilizing the residual gas saturation. Chatzis and Morrow (1984) performed co-current imbibition tests by building relatively high residual oil saturation from forced imbibition using a small external force gradient, and then gradually increasing the pressure gradient until there was some residual oil production. They found that the critical capillary number for mobilizing the residual oil in porous media is about 10^{-5}. Morrow and Songkran (1980) studied the interplay of capillary, viscous and buoyancy forces in the mobilization of residual oil in porous media. Capillary number was investigated at three kinds of different wettability fluids of blobs in sphere packs. Through the experiment work they found the residual saturation varied from normal value of about 14.3% when the Bond number was less than 0.00067 and capillary number was less than 3E-6, down to near zero when either the Bond number exceeded 0.35 or capillary number exceed about 7E-4 for a vertical displacement column.

Imbibition Tests

Flow in porous media mainly includes drainage and imbibition. When the nonwetting phase displaces the wetting phase in a porous medium, the process is called drainage. When a porous medium is partially or fully saturated with a non-wetting phase, and a wetting phase is allowed to invade the porous medium, the process is called imbibition. When the imbibition is dominated by capillary pressure only, the imbibition is called spontaneous imbibition and when some force other than capillary pressure dominates the imbibition, the imbibition is called forced imbibition. When the wetting phase invades the samples from one end of sample and the non-wetting phase (in this case gas) is produced from another end of sample, it is called co-current imbibition. When the wetting phase invades the sample from all different directions and the non-wetting phase (in this case gas) is produced from different directions, it is called counter-current imbibition. In this work, our only concern is forced co-current imbibition tests following spontaneous co-current imbibition tests (Figure 1 and Figure 2).

Water imbibition was monitored through low field NMR. Water saturation change with time and at different flow rates can then calculated through converting the NMR amplitude into mass of imbibed water. Gas saturation was further calculated by difference. The different water flow rates used correspond to the capillary number for water–gas systems. Berea sandstone and a group of Western Canada Sandstone plugs were used to perform all the experiments.

Results

The experiments produced residual gas saturation from spontaneous imbibition. Additional residual gas produced from forced imbibition, which will be a function of capillary number. On-line NMR was used to monitor water accumulation during imbibition through monitoring the signal amplitude increase. Figure 3 and Figure 4 are examples of NMR amplitude changing as water accumulates in the plug and gas saturation change with time, respectively. Figure 5 and Figure 6 are the results of residual gas saturation and normalized residual gas saturation as a function of capillary number. From the overall observations, we concluded that the on-line NMR could be used successfully to monitor water imbibition into a gas-saturated plug. The critical capillary number to remobilize the trapped gas is much smaller than to remobilize the trapped oil.

References Cited

Kantzas, A., M. Ding, and J. Lee, 2001, Residual Gas Saturation Revisited: SPE 75116, Reservoir Evaluation and Engineering, v. 4/6, p. 467-477.

Crowell, D., G. Dean, and A. Loomis, 1966, Efficiency of Gas Displacement from a Water-Drive Reservoir: U.S. Dept. of the Interior, Bureau of Mines, 29 p.

Chatzis, I., and N.R. Morrow, 1984, Correlation of Capillary Number Relationships for Sandstone: Pet. Trans. AIME, v. 277, p. 555-562.

Morrow, N.R., and B. Songkran, 1981, Effect of Viscous and Buoyancy Forces on onwetting Phase trapping in Porous Media: in Surface Phenomena in Enhanced Oil Recovery, D.O. Shah, Editor, Plenum Press, p. 387-411.

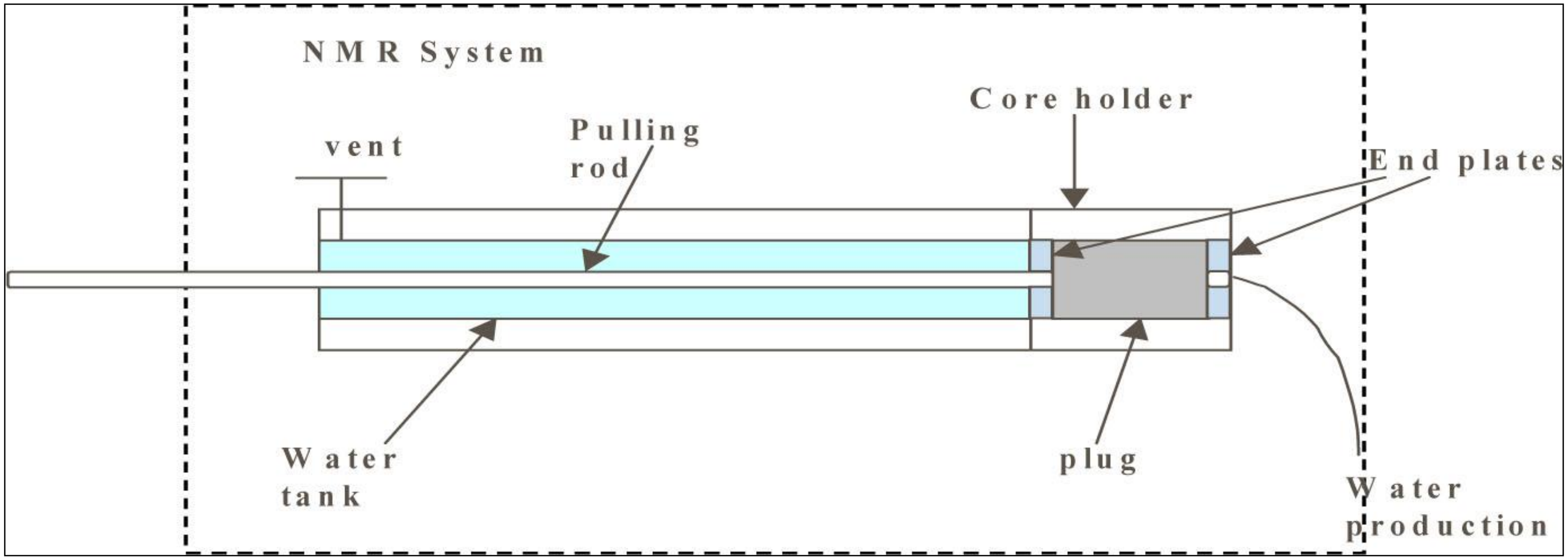

Figure 1. Spontaneous imbibition apparatus in NMR.

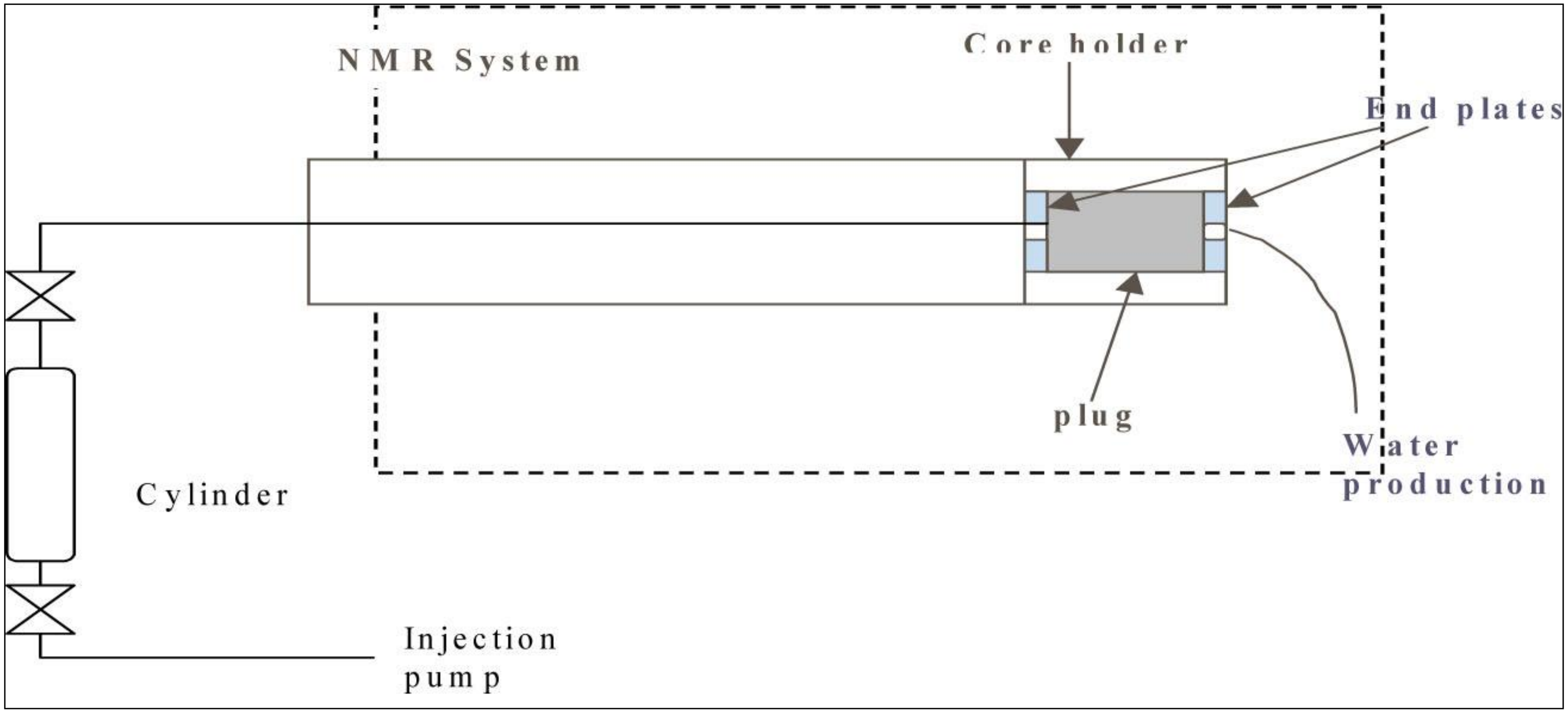

Figure 2. Forced imbibition apparatus in NMR.

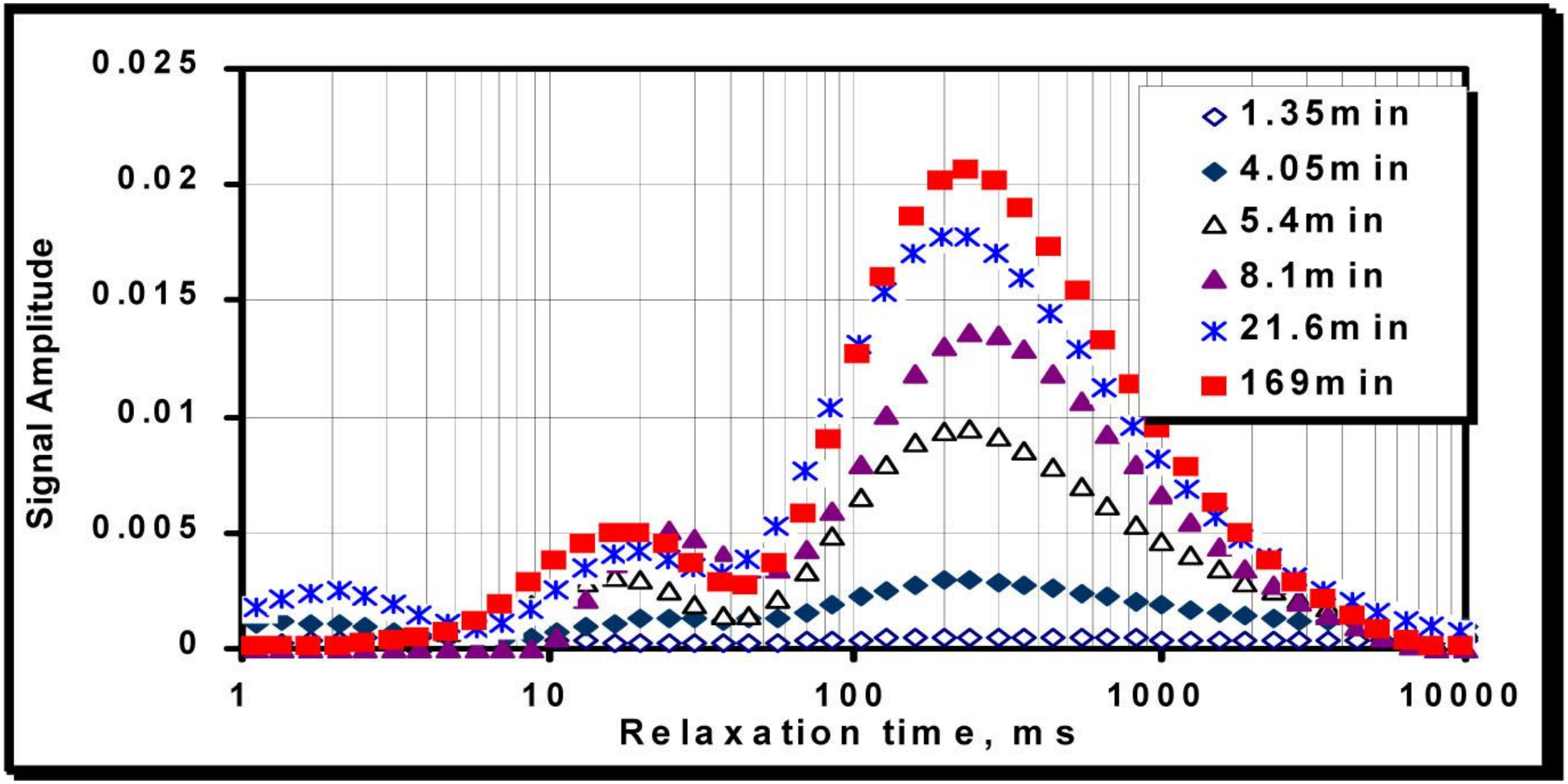

Figure 3. Example of spectra change with time.

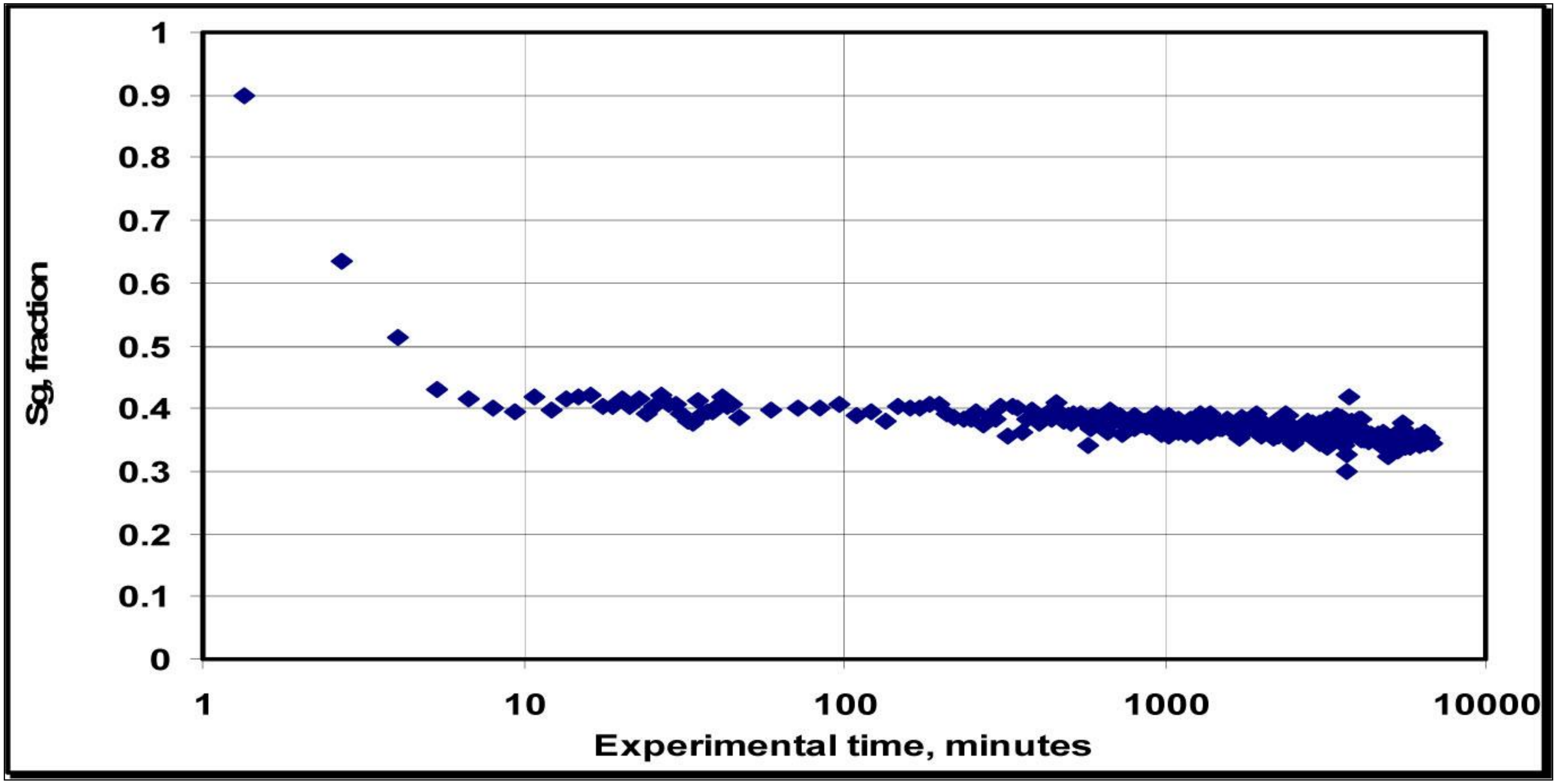

Figure 4. Example of gas saturation change with time.

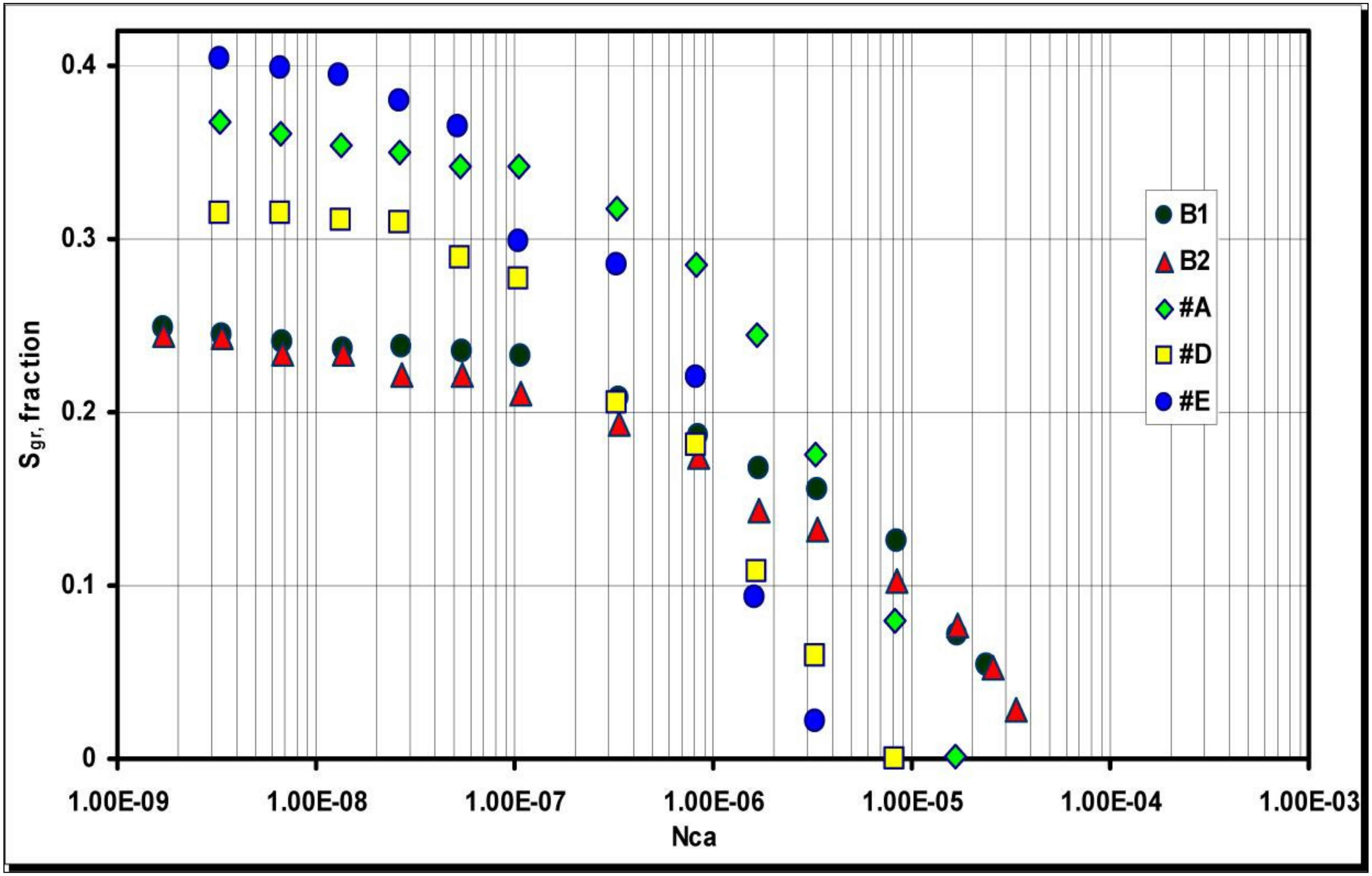

Figure 5. Residual gas saturation change as a function of capillary number.

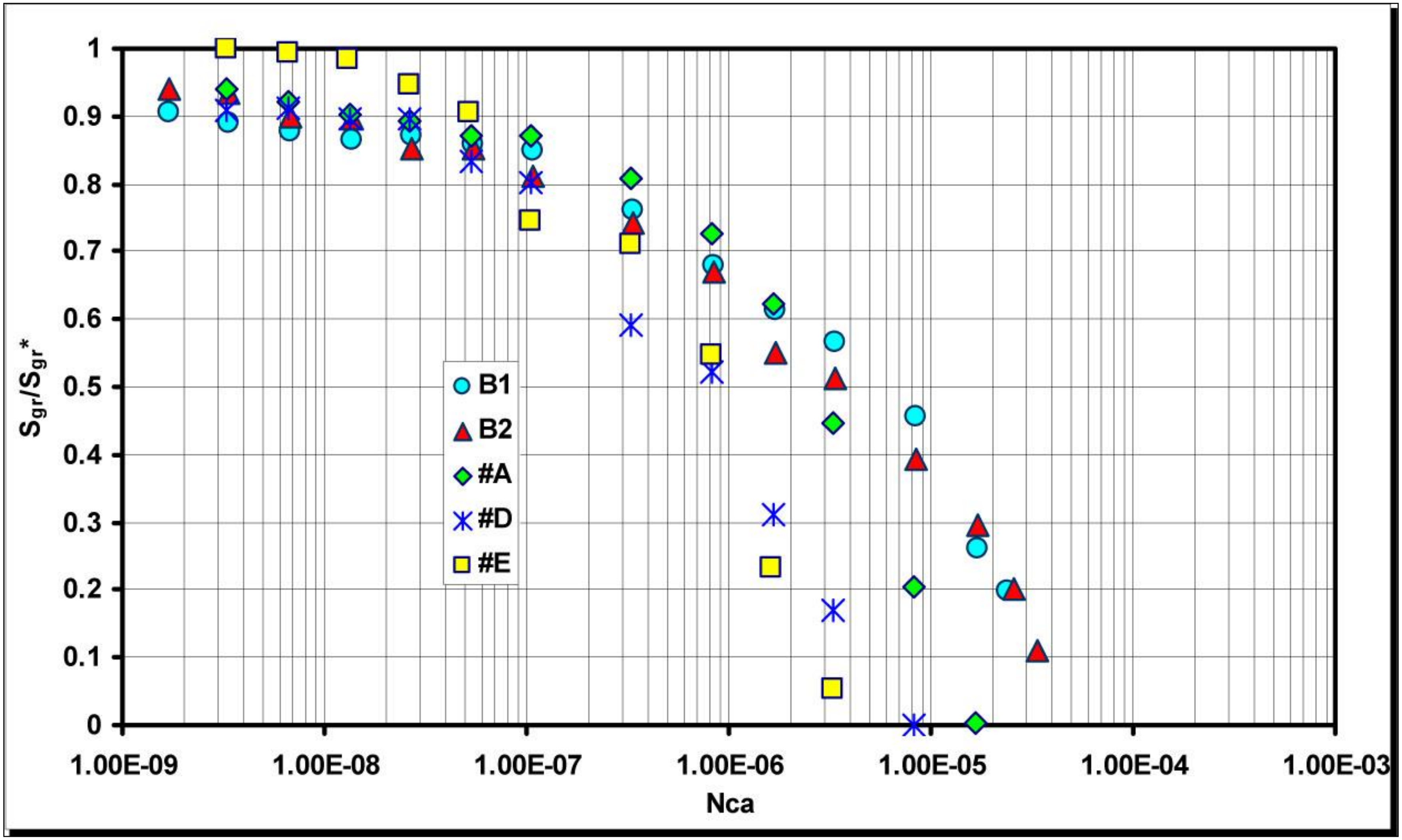

Figure 6. Normalized residual gas saturation as a function of capillary number.