NMR Fluid Typing Using Independent Component Analysis Applied to Water-Oil-displacement Laboratory Data

Pedro A. Romero, Geoneurale, and Manuel M. Rincón, Central University of Venezuela

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Snowmass, Colorado, USA, 21-26 August 2016

ABSTRACT

In low field NMR relaxometry for hydrogen, the T_1 or T_2 spectra of core samples are mixtures of the individual contributions of the saturating phases filling the pore space, either water or hydrocarbon. Fluid typing (identification and quantification of each phase) becomes challenging, however, when individual spectra overlap within a certain relaxation time window.

A traditional fluid typing approach, based on the diffusion effect, is complex and expensive. It requires magnetic field gradient, multiple radio frequencies, and a special fit-for-purpose inversion software. This approach applies to T_2 only; T_1 is not affected by diffusion relaxation mechanisms.

Independent component analysis (ICA) has been tested as a means of solving this problem. ICA is a blind source separation (BSS) technique that yields statistical independent T_2 spectral source components of the present fluids, without previous knowledge of either relaxation mechanisms or fluid properties. The technique can also be applied to T_1.

In a water-oil drainage experiment, beginning with 100% oil saturation, we measured the T_2 spectra of the samples at five water saturation stages, to nearly 97%, and used these spectra as input for the BSS-ICA processing. As output, we obtained the statistical independent T_2 spectra for oil and water and a mixing matrix containing the individual weights that define the measured T_2 spectra at any acquisition step. The results show close correlation between the oil-T_2 ICA-component and the T_2 spectrum of the 100% oil saturated sample. The ICA-derived water saturations show a good match with reported experimental values. The water-T_2 ICA-component shows a bimodal behavior, reflecting the pore size distributions for T_2 shorter than 400ms and the bulk water for T_2 values greater than 1000ms. The bulk relaxation is caused by the presence of remaining oil layers that prevent a magnetic interaction between water molecules and the pore surface.

INTRODUCTION

In reservoir characterization fluid identification is a key element, as it provides very valuable information to determine the strategy for enhanced recovery processes. Specifically, in the Santa Bárbara Field, Eastern Venezuela's, where water injection has been proposed as recovery mechanism, there has been a great interest in improving fluid typing techniques. In this regard understanding the applicability of NMR is considered of high importance [1].

Fluid identification by NMR is a very challenging task, especially when relaxation spectra T_1 or T_2 of the different fluids overlap. Classic examples are extra heavy oil and clay-bound water, heavy oil and capillary-bound water, light oil (including oil-based mud filtrate) and free water at higher T_2 times. In principle, the spectral overlap on T_2 can be solved using Diffusion-T_2 intrinsic (DT_2) maps, where the diffusion as a second dimension can provide a spectral separation of fluids [2]. Unfortunately, many times due to technical limitations of NMR equipment in failing to provide enough frequencies and long enough data sets (echo trains), the applicability of DT_2 maps is limited and unprecise. Given these circumstances and the fact that in the most common scenario only T_2 distributions data are available, the spectral separation using a data-driven method from Machine Learning can become a very important solution.

The BSS-ICA [2] is a Machine Learning approach based on statistical assumptions made on the probability distribution functions of the spectral components -the unknown sources that setup a composed signal. In this work, a BSS-ICA algorithm, *fastica,* is applied to retrieve individual water and oil T_2 spectra from their mixtures in T_2 distributions from core plug samples during a water-oil displacement experiment. The BSS-ICA-derived water saturation at the different water-oil displacement steps is quantified and compared against the reported experimental values.

BLIND SOURCE SEPARATION BASED ON INDEPENDENT COMPONENT ANALYSIS

The BSS-ICA model is based on the assumption that a set of mixtures $[x_1, x_2, \ldots x_n]$ are generated from the linear mixture of n independent source components $[s_1, s_2, \ldots s_n]$, where

$$x_j = a_{j1}s_1 + a_{j2}s_2 + \cdots + a_{jn}s_n = \sum_{k=1}^{n} a_{jk}s_k \qquad (1)$$

and $[x_1, x_2, \ldots x_n]$ and $[s_1, s_2, s_n]$ are considered random. The values of the signals are considered samples (instantiations) of the random variables, not functions of time. In vector matrix notation, the observable variable vector x is expressed as

$$x = [x_1, x_2, \ldots, x_n]^T = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \qquad (2)$$

and the source variable vector s is expressed as

$$s = [s_1, s_2, \ldots, s_n]^T = \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_n \end{bmatrix} \qquad (3)$$

The mixing matrix A, which encodes the estimation of the fluid saturation, is

$$A = \left(a_{ij} \middle| i = 1,n; j = 1,n\right) = \left(a_j \middle| j = 1,n\right) = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix} \quad (4)$$

The linear mixing equation, i.e. the independent component analysis model, the ICA-model, is reduced to:

$$x = A * s \quad (5)$$

Denoting by a_j, the jth column of matrix A, the model thus becomes:

$$x = \sum_{i=1}^{n} a_i s_i \quad (6)$$

The measured data x may be reconstructed by performing the above calculation individually for each source s_i. The fluid saturation at any depth level may be obtained by integrating the area of each spectrum xi = $a_i \cdot s_i$ at its corresponding displacement steps (or sequence). The ICA model is a generative model in that it describes how the observed data are generated by mixing the components s_i. The independent components are latent variables; they are not directly observable. The term "blind" in BSS reflects the fact that very little, if anything, is known in the mixing matrix A, and few assumptions are made with respect to the source signals. Specifically, the basic assumption is that the source components are statistically independent, and hence have unknown distributions as non-Gaussian as possible, to optimize a certain contrast function. The best W is found, where W is the unmixing matrix that yields

$$y = Wx \quad (7)$$

which is the best estimate of the independent source vector.

If the unknown mixing matrix A is square and non-singular, then

$$W = A^{-1} \text{ and } s = y \quad (8)$$

Otherwise, the best unmixing matrix that separates the sources is given by the generalized inverse Penrose-Moore matrix

$$W = A^{+} \text{ and } \|s - y\|s = min \quad (9)$$

The BSS-ICA algorithm used in this work is *fastica* [3].

THE EXPERIMENT

To test the hypothesis whether it is possible to calculate the water saturation (Sw) from BSS-ICA applied on T_2 distributions, data from an oil-water displacement experiment on core plugs has been used. Two core plugs of 1x1.5 inches' size were selected from the mega porosity facies, considered the best in terms of storage and drainage capacity.

Table 1. below shows some petrophysical chraracteristic parameters of these core samples.

Table 1. Petrophysical characteristics of samples A and B

Sample	Porosity [%]	Permeability [mD]	Swi [%]	BVI [%]	FFI/BVI	T2cutoff [ms]
A	15.3	1038.3	9.5	6.4	14.6	47.4
B	13.7	635.1	12.3	11.7	7.5	68.6

Starting with 100% So, the oil was gradually displaced by water in a centrifuge experiment. For the NMR measurements the sample was taken from the centrifuge at 4 different water saturation levels. For reference, the oil T_2 distribution was also measured inside the core samples (100% So). Table 2. shows the characteristics of the oil samples used in each displacement experiment for core plug A and core plug B.

Table 2. Displacement Parameters

Displacement Parameters	Sample A	Sample B
Oil viscosity	Lower	Higher
T_2 oilpeak inside sample/outside (bulk) [ms]	350/610	235/415

Figures 1.a and 1.b show the T_2 distributions for sample A and B respectively. The water saturation is shown as a parameter calculated from the centrifuge experiment data. The first T_2 distributions at the top of each figure correspond for the 100% water saturated sample (blue) and for 100% oil saturation (red). These spectra are considered only for reference purposes, but not used as input for the ICA approach. For each core sample A and B the T_2 distributions at different levels of water saturation, were used as block input for the BSS-ICA model.

The *fastica* algorithm takes as input the 4 individual T_2 spectra of each core sample data set and estimates 2 IC's as output, which are interpreted as the oil and water spectral sources. The estimated oil saturation at any of the 4 stages of the experiment is calculated as the area under the IC-oil spectrum times its corresponding weight in the mixing matrix A. The complement value to it yields the water saturation, which is later compared against the assumed true value calculated from the displacement experiment.

RESULTS AND DISCUSSIONS

The results of applying BSS-ICA with 4 T_2 distributions as input and 2 IC's as output reflecting the oil and water sources, can be seen in Figures 2a. and 2b. for each core plug sample. It is worth noticing that the water distributions show two peaks corresponding one to the S/V relaxation and the other to bulk relaxation. In the oil spectra, the secondary peak at higher T_2 times is due to lack of separation power of the algorithm given the relatively poor statistics of the input data.

The numerical results of the BSS-ICA for sample A and sample B are shown in Table 3. and Table 4. respectively.

Table 3. BSS-ICA results for sample A

Measure. No.	NMR-Porosity	Sw Displacem.	Sw BSS-ICA
1	14.2	16.7	X
2	16.3	41.9	38.4
3	17.2	58.7	56.6
4	16.5	71.3	81.4

Table 4. BSS-ICA results for sample B

Measure. No.	NMR-Porosity	Sw Displacem.	Sw BSS-ICA
1	12.6	39	40.8
2	14.1	56.2	62.5
3	13.6	77.9	72.2
4	14.0	86.7	72.3

Despite of experimental errors due to the non-uniform fluid distribution along the core plug longitudinal axis and missing hydrogen index correction, the results show that *fastica* can be used to obtain a good estimate for the water saturations of the samples.

Figure 3. shows the comparison between the water saturation as calculated from the displacement experiment and the values derived from BSS-ICA, using only the non-negative part of the spectra.

Theoretically, an improvement of results can be achieved by increasing the statistics of the input data with more NMR measurements at different water saturation levels, but with detrimental effect on the experimental time. Performing the displacement experiment inside the NMR resonator could be an interesting option to pursue as it would also mimic the wellbore scenario in the invading zone.

CONCLUSIONS

The BSS-ICA is a powerful tool for fluid typing from NMR T_2 distributions. The retrieved independent components match well with the expected oil and water T_2 spectra, validating the undelaying ICA-model.

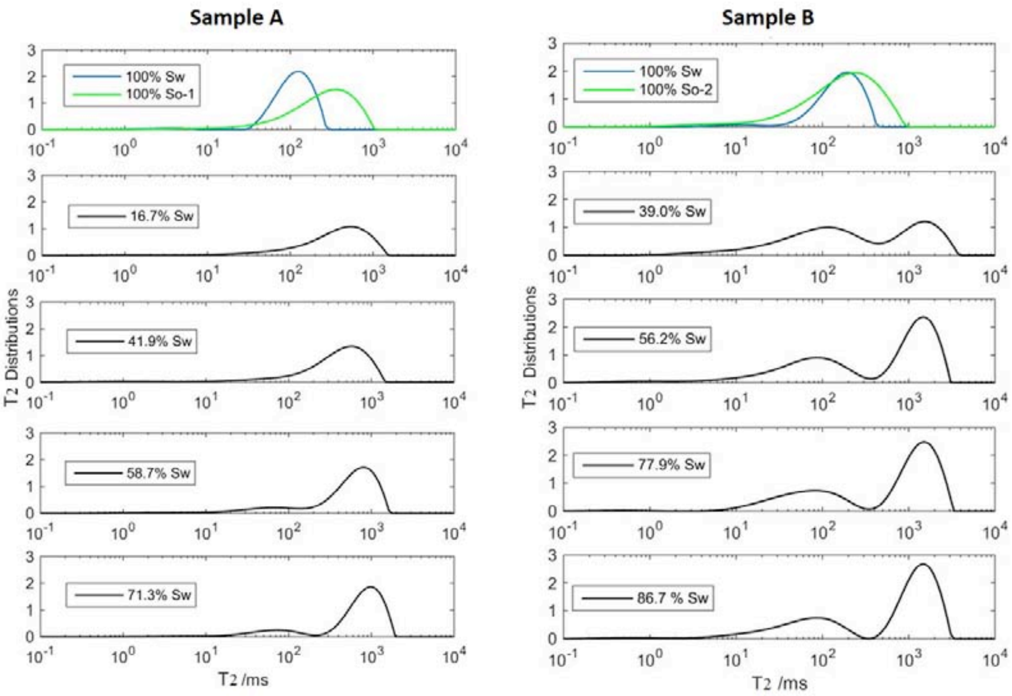
The BSS-ICA water saturation shows a good agreement with the values from the displacement experiment, specially in the range between 20% – 80%. At lower or higher water saturation values, a non homogeneous fluid distributions along the longitudinal axis may cause greater errors in the BSS-ICA estimated water saturation.

ACKNOWLEDGEMENTS

The authors thank the Central University of Venezuela and PDVSA for supporting the BSc. thesis of Manuel Rincón.

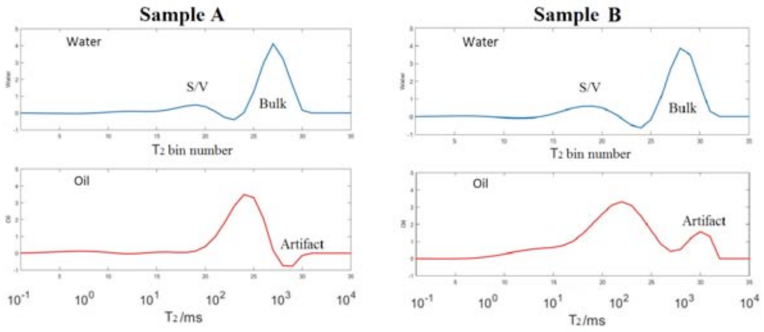
REFERENCES

1. Rincón, M., “Identificación de petrofacies y fluidos de formación a partir de resonancia magnética en tapones de núcleos de pozos del miembro Naricual Inferior, Campo Santa Bárbara, Norte de Monagas”, BSc. Thesis, Central University of Venezuela, Caracas, Venezuela, May, 2004.
2. Romero, P., Q. Zhang, “Fluid Typing from NMR Logging with a Gradient Magnetic Field”, 2010 Rio Oil & Gas Expo and Conference, Rio de Janeiro, Brazil, 13-16 September, 2010.
3. Romero, P., “Nuclear Magnetic Resonance Evaluation Using Independent Component Analysis (ICA)-Based Blind Source Separation”, Pub. No.: WO / 2009 / 038744, Pub. Date: March, 26th, 2009, Int. Appl. No.: PCT / US2008 / 010867 2009.
4. Hyvärinen, A., J. Karhunen and E. Oja. “Independent Component Analysis”, John Wiley & Sons, Inc, New York Inc. (2001).



(a) (b)

Figure 1. T_2 distributions of samples A and B.



(a) (b)

Figure 2 Water and oil IC-T_2 of samples A and B.

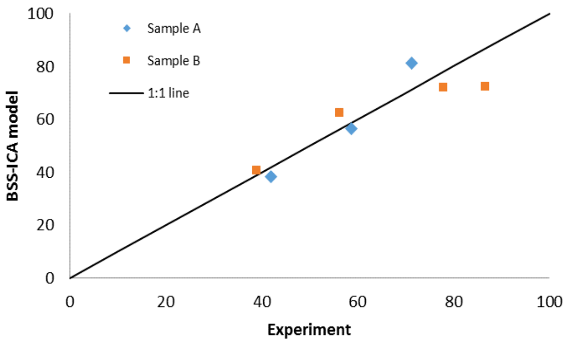


Figure 3. Water saturations from BSS-ICA vs. displacement experiment.