

# LOW FIELD NMR AS AN ALTERNATIVE TECHNIQUE TO ESTIMATE OF DENSITY AND VISCOSITY IN TOLUENE-HEAVY OIL MIXTURES

## ■ RMN DE BAJO CAMPO COMO UNA TÉCNICA ALTERNATIVA PARA ESTIMAR LA DENSIDAD Y VISCOSIDAD EN MEZCLAS DE TOLUENO-ACEITE PESADO

María Sandoval M<sup>a</sup>, Herin Valderrama P<sup>a</sup>, Miranda Sánchez M<sup>a</sup>, Daniel Molina V<sup>b</sup>, Samuel Muñoz N<sup>a</sup>

### ABSTRACT

The success of low field Nuclear Magnetic Resonance (LF-NMR) to estimate heavy oil properties depends on a good selection of mathematical models and fitting parameters. Since the correlations proposed are not universally applicable, in this study, a NMR published model was chosen and tuned to determine the density and viscosity of several mixtures of a Colombian heavy oil with toluene. The process began by mixing toluene with heavy oil to obtain several measuring points with properties similar to those of heavy oils. Each mixture was taken to a 7.5 MHz spectrometer at 40 °C, where NMR parameters were acquired and used in the five pre-selected mathematical models. The reliability of viscosity measurements was analysed with the root mean square error (RMSE) and maximum absolute error (MAE). After the NLS regression process, the most accurate prediction was reached through the Burcaw model, with RMSE values of 40.55 cP. On the other hand, the density was estimated with the Wen correlation with results showing a relative error percentage of less than 1%. According to such error values, the tuned models are considered a starting point to extend the NRM technique use to other Colombian heavy oils with low uncertainty levels.

### RESUMEN

El éxito de la RMN para estimar las propiedades del petróleo pesado depende de una buena selección de los modelos matemáticos y los parámetros de ajuste. Dado que las correlaciones propuestas no han resultado ser de aplicación universal, en el estudio actual, se eligió un modelo de RMN publicado y se ajustó para determinar la densidad y viscosidad de varias mezclas de un crudo pesado colombiano con tolueno. El proceso comenzó mezclando tolueno con el crudo pesado para obtener varios puntos de medición con propiedades similares a los crudos pesados. Cada mezcla se llevó a un espectrómetro de 7,5 MHz a 40 ° C, donde se adquirieron los parámetros de RMN y se emplearon en los cinco modelos matemáticos preseleccionados. La confiabilidad de las mediciones de viscosidad se analizó con la raíz del error cuadrático medio (RMSE) y el error absoluto máximo (MAE). La predicción más precisa se alcanzó con el modelo de Burcaw, después del proceso de regresión NLS, con valores de RMSE de 40,55 cP. Por otro lado, la densidad se estimó con la correlación de Wen y los resultados mostraron un porcentaje de error relativo menor al 1%. De acuerdo con esos valores de error, los modelos ajustados en este trabajo se consideran un punto de partida para extender el empleo de la técnica NRM a otros petróleos pesados de Colombia con bajos niveles de incertidumbre.

### KEYWORDS / PALABRAS CLAVE

NMR | Heavy oil | Liquid solvents | Viscosity | Density  
RMN | Crudo pesado | Solvente líquido | Viscosidad | Densidad

### AFFILIATION

<sup>a</sup>Grupo de investigación Recobra Mejorada, Escuela de Petróleos,  
<sup>b</sup>Laboratorio de Resonancia Magnética Nuclear, Universidad Industrial de Santander, Apartado Aéreo 678, Bucaramanga, Colombia.  
\*email: maria.sandoval@correo.uis.edu.co

## 1. INTRODUCTION

The analysis and estimation of the physicochemical properties of heavy oils such as density, viscosity, API gravity, and molecular weight, play a crucial role in the characterization of oil, and are necessary in upstream, downstream, and midstream activities of the hydrocarbon industry[1]. Although density is key to evaluate resources, viscosity is the property that most affects productivity and heavy oil recovery[2][3]. Moreover, these properties are directly involved in the optimization of oil refining operations, the determination and quality control of derivatives, the estimation of transport and storage conditions[4], the development of reservoir simulation processes[1], and the selection of a suitable oil recovery. However, measurements with conventional techniques take time, usually requiring tedious and expensive experimental processes, where accuracy decreases as oil viscosity increases, as equipment designs and protocols are focused on light and medium oils [5] [4]. Furthermore, human error in these measurements occurs more frequently and reflects a low reliability level in the characterization of oil, leading to failures in equipment designs for facilities, numerical simulations, and evaluation of reservoirs[6].

Low field NMR is proposed to overcome these difficulties. It is a novel technique that allows for indirect estimation of multiple properties of fluids, such as viscosity and density [7][8][9][10][11], API gravity[12], molecular weight[4], aromatic content[6], total acid number and sulphur content[13], through mathematical models developed.

The success of LF-NMR measurements depends on the mathematical model. Several models have been developed to estimate oil viscosity and density using NMR spectra. For instance, Bryan et al. [21] developed a viscosity model from different reservoirs in Canada to estimate viscosity in the range of 1 to 3,000,000 cP for temperatures between 25 and 85 °C. In 2008, Burcaw et al. showed a correlation between the logarithmic mean of the transverse relaxation time

( $T_{2gm}$ ) and the hydrogen index (HI). The Burcaw model is suitable for oils with maximum viscosity of 107 cP. Vinicius (2014) developed a viscosity and °API gravity model using the transverse relaxation time ( $T_2$ ) and relative hydrogen index (RHI). The Vinicius model showed a good degree of reliability on 50 samples with viscosity ranging from 23.75 to 1801.09 cP and °API gravity from 16.8 to 30.6. Markovic et al (2020) related the viscosity with the Hydrogen index (HI) and the logarithmic mean of the transverse relaxation time ( $T_{2gm}$ ). The Marcovic model was developed with a suite of 23 Canadian heavy oils recovered from different reservoirs, with a wide range of temperatures (26–200 °C) and viscosity (70–21,600 cP).

The required LF-NMR measurements are simple and non-destructive, capable of providing a large amount of valuable information about the fluids studied from a small sample [7][9][14]. In addition, the LF-NMR technique offers the possibility of performing either laboratory or in situ measurements with borehole logging tools, making this a more attractive technique[15][16]. However, LF-NMR measurements depend on the oil properties and the details of data acquisition[9] [17]. Moreover, the above models have default parameters derived for heavy oils from a certain field and, when applied to different heavy oils, considerable prediction errors[18] occur. Hence, the models must be customized for each NMR equipment and fluids group.

Therefore, for purposes of this research, the mathematical models proposed in literature were evaluated to estimate the density and viscosity of heavy oil by low field NMR. The main objective was to adjust the selected models to properties of a Colombian heavy oil and to show the LF-NMR quantitative and qualitative abilities as compared with conventional techniques. The tuned models and the comparison study will be a starting point to extend the use of the NMR technique to other Colombia heavy oil with a low uncertainty level.

## 2. EXPERIMENTAL DEVELOPMENT

In this section the workflow to evaluate the NMR models in literature and to determine the density and viscosity of the mixture toluene and Colombia heavy oil (Figure 1) is explained.

### OIL-SOLVENT MIXTURES PREPARATION

Toluene was selected as liquid solvent due to its dilution efficiency and capability of interfering in asphaltene aggregation processes and producing homogeneous mixtures with heavy oil. For preparing the samples, Colombian heavy oil (12 °API and water content <1%) and toluene were combined to obtain a mixture with a solvent concentration of 0%, 2%, 4%, 6%, 8%, 10% y 12% m/m. These proportions were selected to achieve properties similar to those of heavy oil, i.e, the viscosity range was between 100 and 10,000 mPa.s and the gravity was between 22.3 and 10 ° API[19].

Initially, the heavy oil sample was thermalized in an electric oven for 2 hours and then poured directly into a flask to prepare the mixtures with toluene. Next, the oil-solvent samples were shaken for 3 hours and then heated at 40°C. Finally, the blends were transferred into NMR tubes.

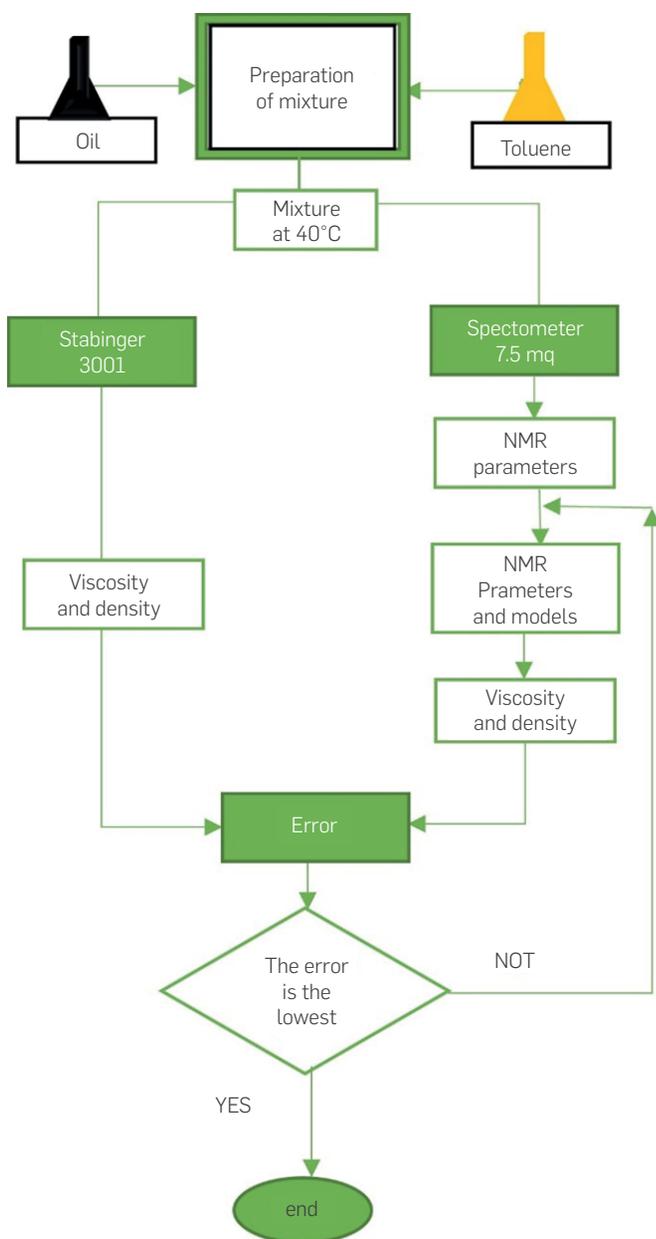
### NMR ANALYSIS

The mixtures were characterized using a Bruker relaxometer of the Minispec mq series, with a frequency of 7.5 MHz. The samples were stabilized at 40°C, which is the equilibrium temperature of the magnet bore.

The Car-Purcell-Meiboom-Gill (CPMG) pulse sequence was used to determine transverse relaxation time ( $T_2$ ). The acquisition parameters of the equipment for the CPMG pulse sequence were: 5000 echoes, 32 scans, 0.5 ms between echoes and 15 s recycling, for a mass of 6 g per sample. The Inverse Laplace Transform (ILT) was applied to the NMR measurements to invert the multi-exponential decays, and to obtain the  $T_2$  distributions with the dynamics center software.

### VISCOSITY AND DENSITY DETERMINATION

The viscosity and density of the samples were determined in a conventional way with a Stabinger 3001 viscometer from Anton



**Figure 1.** Workflow to evaluate NMR model and to determine the density and viscosity values

Paar at 40°C, under ASTM D7042 standard [20]. The repeatability and reproducibility percentages reported by the standard were 0.1% and 0.54% for viscosity and 0.03% and 0.14% for density tests.

### NMR MODELS EVALUATION

The NMR models with default parameters found in the literature, were used to estimate viscosity and density with the NMR results obtained in each test. The values determined were compared with the information from Stabinger 3001 by error calculations. When the error values were significant, the NLS regression was performed to tune the NMR model and thus achieve optimal values for their empirical constants (Figure 1).

For viscosity measurements, the NMR models accuracy was assessed visually on linear regression plots and by comparing coefficients of determination –  $R^2$ . Moreover, the root mean square error (RMSE) and the maximum absolute error (MAE) of the predictions were calculated as statistical metrics, due to the wide range of viscosity in existing research (Table 1). The MAE represents the largest absolute difference between predicted and observed viscosity values. The RMSE is the square root of the differences between predicted values and observed values or the quadratic mean of these differences. As for density, the parameter selection was based on the lowest percentage of relative error due to its small-scale values (Table 1).

## 3. RESULTS AND DISCUSSION

### VISCOSITY AND DENSITY ESTIMATION WITH CONVENTIONAL METHODS.

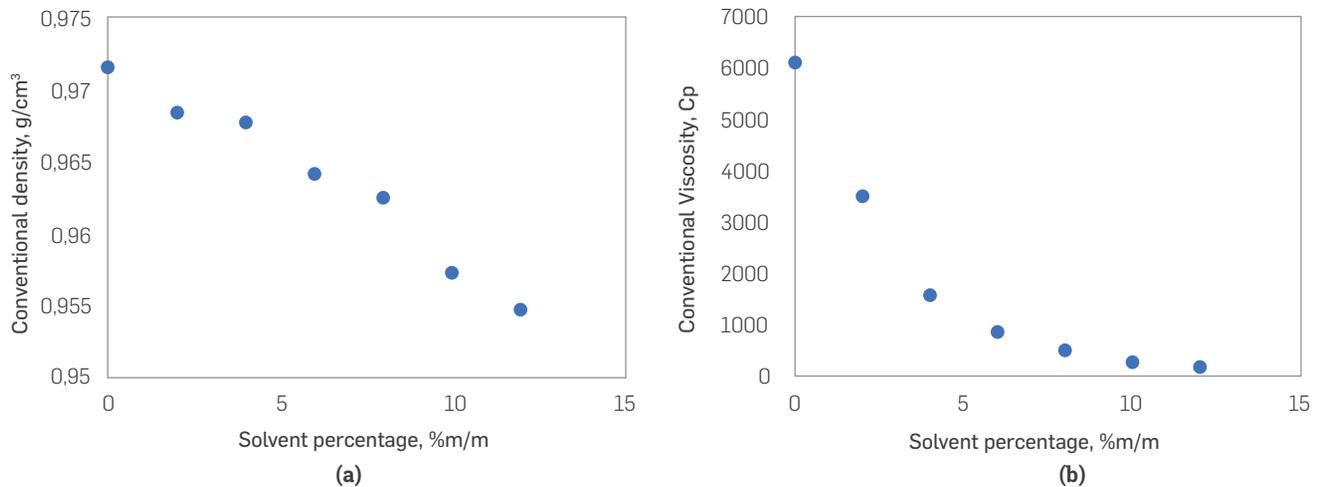
Table 1 summarizes the estimated experimental results by the Stabinger viscosimeter as a conventional method. The measurements of the eight (8) samples represented the real value, which was used to calculate the error percentages and the deviations of the obtained values with LF-NMR.

**Table 1.** Viscosity and density results by conventional technique

ID	Toluene concentration [%m/m]	Viscosity		Density
		[cP]	[mm <sup>2</sup> /s]	[g/cm <sup>3</sup> ]
		40 °C	40 °C	40 °C
M0	0	6105.5	6284.4	0.97154
M2	2	3498.5	3612.7	0.96837
M4	4	1571.8	1624.3	0.96768
M6	6	858.74	890.72	0.9641
M8	8	502.71	522.34	0.96243
M10	10	269.03	281.07	0.95719
M12	12	176.53	184.92	0.95463
M100	100	0.8613	1.019	0.84481

Figure 2a shows a linear dependence between the density and the amount of toluene, indicating that for each gram of toluene added the density decreases by approximately 0.0011 g / cm<sup>3</sup> at a temperature of 40 °C

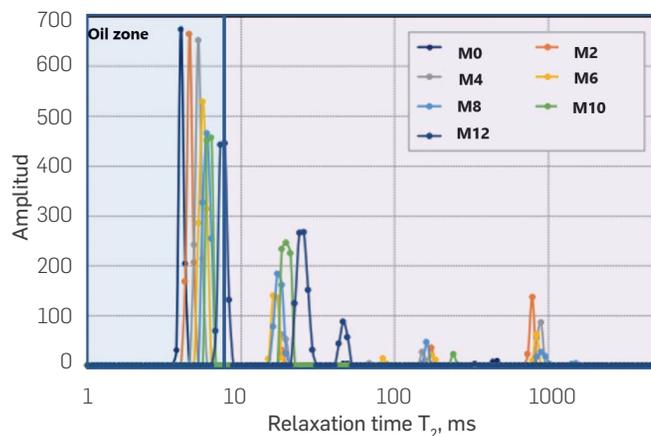
On the other hand, Figure 2b shows the magnitude of the reduction in viscosity due to the addition of this solvent. It is observed that by adding a small amount of toluene, there is material reduction of viscosity. However, the viscosity reduction percentage is lower at a higher toluene concentration. Hence, it allows to ensure that in the dilution process, the solvent efficiency is not proportional to the amount of solvent, since at a solvent added concentration greater than 12%, the viscosity reduction is not meaningful.



**Figure 2.** Mixtures density and viscosity relation with the toluene concentration.

### NMR PARAMETERS ANALYSIS

The results obtained from NMR are distribution curves, as those shown in **Figure 3**. The distribution curves relate the amplitude with relaxation time  $T_2$  and show different behaviours in each sample analysed. The relaxation time distribution of **Figure 3**, suggests that as the amount of toluene added increases, the amplitude of the mixture decreases in the oil zone, i.e. at  $T_2$  less than 10 ms [11], and towards the right region of the relaxation distribution, the amplitude of peaks that represent the light fractions raise.



**Figure 3.** Relaxation time distribution graph for all samples

Before estimating the properties of the fluids with NMR, it was necessary to analyze the relationship of the NMR parameters (RHI and  $T_{2gm}$ ) with conventional density and viscosity measurements to select the most appropriate model.

First, the geometric mean of  $T_2$  ( $T_{2gm}$ ) was estimated, using equation 1 and the information of **Figure 3**:

$$T_{2gm} = e^{\left(\frac{\sum A_i \ln(T_{2i})}{\sum A_i}\right)} \quad (1)$$

Where:

- $T_{2gm}$ : The geometric mean of  $T_2$
- $A_i$ : Amplitude for each  $T_{2i}$
- $T_{2i}$ : Relaxation time of each point.

Next, the Amplitude Index (AI) was calculated:

$$AI = \frac{\text{fluid Amplitud}}{\text{fluid mass}} \quad (2)$$

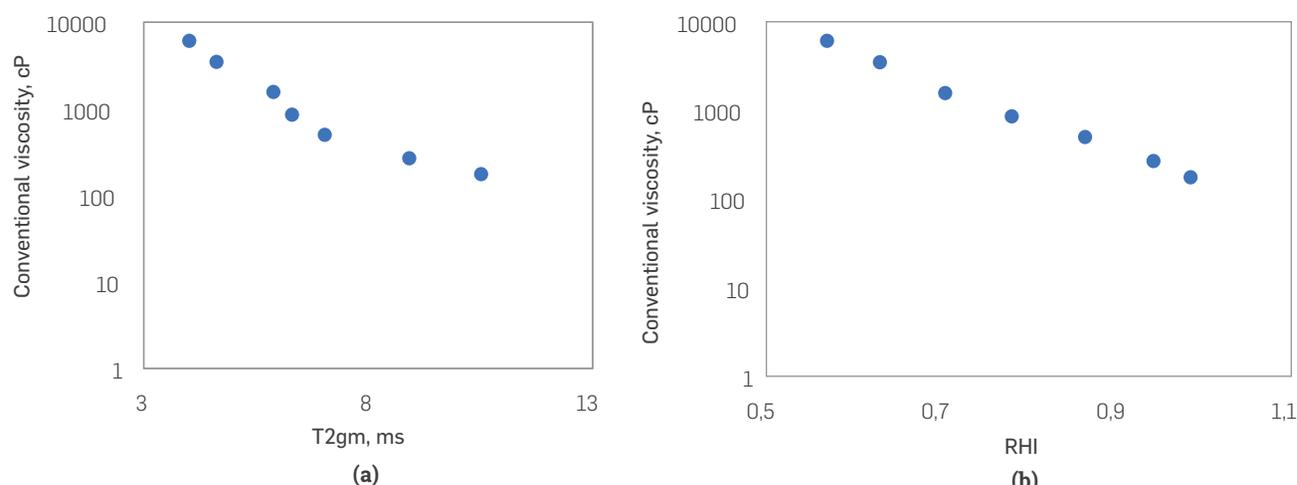
The amplitude index allowed to calculate the Relative Hydrogen index (RHI). The RHI provides information on the amount of hydrogen in a sample with respect to the amount of hydrogen in a water sample, by relating the amplitude index of the sample ( $AI_{sample}$ ) with the water amplitude index ( $AI_{water}$ ) through equation 3.

$$RHI = \frac{AI_{sample}}{AI_{water}} \quad (3)$$

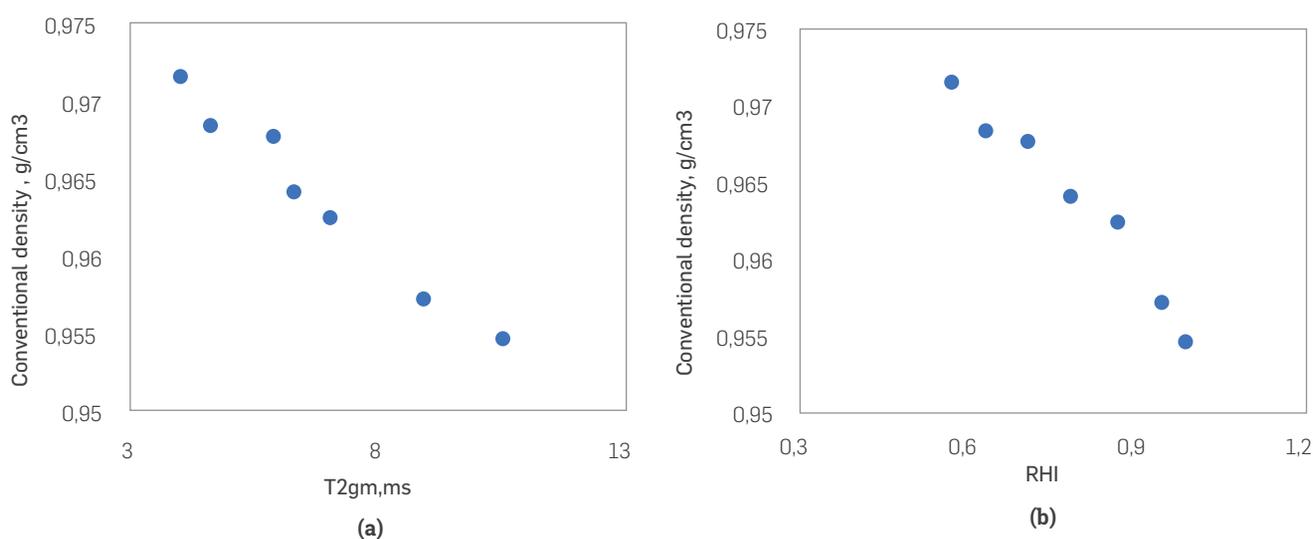
The relationship of the NMR parameters with the viscosity and density are presented in **Figures 4** and **5**, respectively.

The first analyzed NMR parameter is relaxation transversal time.  $T_2$  increases as the function of viscosity decreases, as reported in the literature [11][7]. As shown in **Figure 4a**, a mixture with a high viscosity (low concentration of toluene) tends to have a very small  $T_2$ , due to the high molecular weight and the closeness of its molecules, relaxing very fast. Likewise, **Figure 4b** shows that the Relative Hydrogen Index raises as viscosity decreases, as the amount of hydrogen becomes higher as the solvent concentration increases in the mixtures.

Further, **Figure 5** presents the relationship between density and NMR parameters. The first analyzed parameter was  $T_{2gm}$  (**Figure 5a**), where its value increased by decreasing the density in the samples. Therefore, the relaxation time values increased, when the number of light compounds (hydrocarbon) raised in the mixtures. As regards the Relative hydrogen Index (RHI) in **Figure 5b**, as solvent concentration and the mixture density increased, the content of hydrogen atoms in the sample and the amplitude values decreased.



**Figure 4.** Relationship of the NMR parameters (a) Viscosity vs T2gm (b) Viscosity vs RHI



**Figure 5.** Density relationship with NMR parameters. (a) Density vs T2gm (b) Density vs RHI

Then, a multivariable regression was performed to relate the viscosity and density from the information obtained with the NMR relaxation times distributions through an ANOVA analysis. The results show the Pvalue estimated for the density and viscosity model with a significance level of 5% as 0.0003 and 0.0006, respectively (Equations 4 and 5). Those values confirm a statistically significant relationship between the NMR parameters (RHI and T2gm) and the fluids properties evaluated.

$$\begin{aligned} \text{Density} &= 0.987224 - 0.00147528 * T_{2gm} \\ &\quad - 0.01732466 * RHI \\ R^2 &= 0.983 \end{aligned} \quad (4)$$

$$\begin{aligned} \text{Log}_{10}\text{Viscosity} &= 5.78086 - 3.53837 * RHI \\ &\quad - 0.00548998 * T_{2gm} \\ R^2 &= 0.988 \end{aligned} \quad (4)$$

Finally, the figures and trends evidenced the strong relationship between the viscosity and density with RHI and T2gm, such as the models shown in the literature to evaluate the properties of heavy oils and mixtures [12][9][8][21][7][10]. However, the models are not universally applicable. They can be affected by the magnetic field of the equipment, the acquisition parameters, and the fluid properties [9]. These have been adjusted mainly to Canadian heavy oils and specified NMR equipment features. Hence, the model constants must be customized for a Colombian heavy oil and the NMR equipment used in this research, as a first step in the characterization of Colombian fluids with LF-NMR.

#### VISCOSITY ESTIMATION BY NMR

Based on the relationship between viscosity and NMR parameters, the models with the  $T_{2gm}$  and RHI were used as input parameters. The models are listed in Table 2, with the number of fitting (free) parameters and recommended conditions.

Where:

**Table 2.** Tested literature NMR Viscosity correlations

Model	Fitting parameters	Equation	Default parameters	Range of viscosity (cP)	Range of temperature (°C)
Bryan, 2003 [21]	2	$\eta = \frac{\alpha}{(RHI)^\beta * T_{2gm}}$	$\alpha$ and $\beta$ (see table 3)	1–3*10 <sup>6</sup>	25-80
Burcaw, 2008 [9]	2	$\eta = \frac{\exp(m)}{(exp)^{s*HI} T_{2gm}}$	$m=16.3$ $s=9.3$	70–21600	10-100
Vinicius, 2014 [12]	2	$\frac{RHI}{T_{2gm}} = a' \eta + b'$	$a'=1.368*10^{-4}$ $b'=0.001$	23.75–1801.09	27.5
Markovic, 2020 [8]	4	$\eta = \frac{a}{(HI)^a T_{2gm}} + c T_{2gm}^{-d}$	$a=515$ $b=9.33$ $c=3645$ $d=1.17$	70–21,600	30-50

$\eta$ : Viscosity (Cp)

RHI: Relative hydrogen index (ad)

$T_{2gm}$ : The geometric mean of T2 (ms)

HI:  $\rho_o/\rho_w * RHI$

$\rho_o$ ,  $\rho_w$ = oil and water density (g/cm<sup>3</sup>)

First, the Bryan model [21] was studied. To choose  $\alpha$  and  $\beta$  constants, the values reported by Bryan et al. [21], Wen et al., [7], Bryan et al. [11] are listed in **Table 3**. Next, each value was used to calculate the viscosity, and the constants with lower error were used to analyze the model.

**Table 3.** Experimental values of  $\alpha$  &  $\beta$  found in the literature for heavy crude oils diluted with solvents.

ID	$\alpha$	$\beta$	ID	$\alpha$	$\beta$	ID	$\alpha$	$\beta$
S1	700.6	5.8799	S9	1998.7	4.7831	S17	3172.7	7.4862
S2	703.0	4.8400	S10	2022.0	4.4700	S18	3648.2	7.6407
S3	1150.0	4.5500	S11	2215.7	5.1928	S19	3799.4	2.9762
S4	1198.0	7.6800	S12	2573.7	7.6407	S20	3810.4	6.2026
S5	1411.0	5.3700	S13	2613.0	4.7300	S21	4348.8	3.7721
S6	1442.5	4.7593	S14	2805.2	4.8982	S22	4889.8	3.0007
S7	1693.9	5.2920	S15	2972.8	8.2605	S23	7867.2	2.5966
S8	1749.0	4.6900	S16	3105.8	7.6947	S24	18620	2.1300

The best fit was achieved through the set of data S8 that corresponded to the values 1749 and 4.69 for  $\alpha$  and  $\beta$ , where MAE, RMSE and determination coefficient (R2) were 40.96 cP, 73.07 cP and 0.99, respectively (**Figure 6** and **7**). Despite the good match with the selected parameters, the NLS linear regression was considered to reduce the error (**Figure 6a**). The results present that the best fit is achieved with  $\alpha$  and  $\beta$  values of 1834.85 and 4.6 respectively. The MAE and RMSE were slightly reduced to 35.02 mPa.s and 65.06 mPa.s after regression, as it is depicted in **Figure 7**.

For the Burcaw [9] and Marcovic [8] model only one set of data for the fitting parameters was found in the literature (**Table 2**). Nevertheless, with these parameters scattered data (**Figure 6a**, blue points), high MAE and RMSE were obtained for both models (**Figure 7**). **Figures 6b** and **6c** show that most predictions did not fall within a factor of one (solid black line).

Therefore, it was necessary to use the NLS regression with the GRG nonlinear method to determine optimal parameters for the 7 samples. For the model Burcaw, the results showed that the lowest MAE and RMSE were reached with  $m$  and  $s$  values of 13.68 and 6.54, respectively (**Figure 5a** red points). Likewise, for the Marcovic model, the best values to  $a$ ,  $b$ ,  $c$  and  $d$  were 1084.2, 5.16, 10031.2 and 2.3, respectively.

**Figure 7** shows that Burcaw [9] and Marcovic [8] RMSE and MAE values were several times lower after tuning the parameters. Moreover, most predictions fall within a factor of one and the determination coefficients (R2) were 0.997 and 0.998, respectively (**Figure 6b** and **6c**).

Vinicius model [12] model was not analyzed due to the properties of the fluids and given temperature conditions, as this mathematical expression is valid for viscosity ranges between 23.75 cP and 1801.09 cP, and RHI values of 0.94 and 1.18 at 27.5 °C.

The most accurate prediction was reached with the Burcaw model in the conditions given, but only after the NLS regression. In comparison with Bryan et al. and Markovic et al., Burcaw et al. had a 24.52 mPa.s and 51.09 mPa.s lower RMSE score, respectively, while the MAE score was 0.93 mPa.s and 15.57 mPa.s lower, respectively.

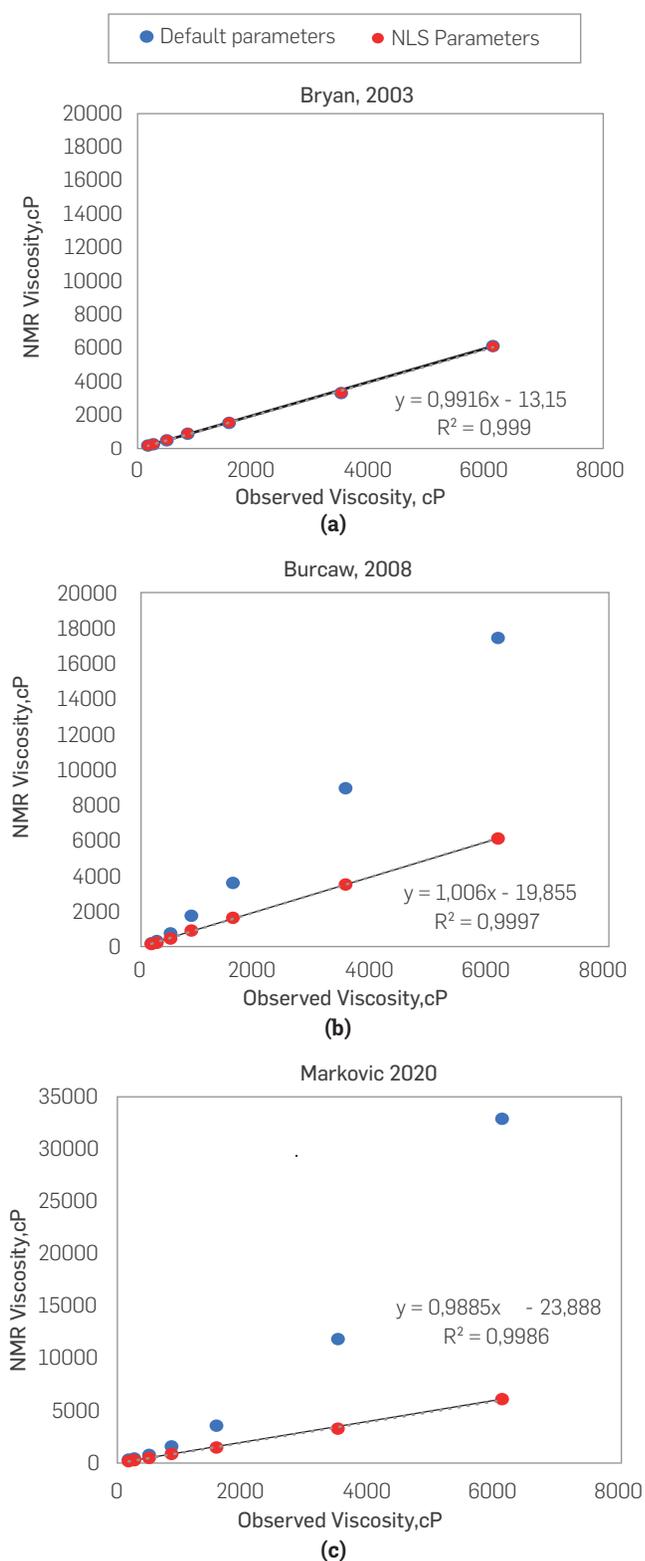
Bryans model could also be a good option to determine the viscosity of heavy oil with toluene since it showed a slightly higher error (RMSE and MAE) as compared with the Burcaw model.

It showed a good fit with the properties of Colombian heavy oil and the NMR equipment specifications, even before NLS regression, by using literature parameters. Therefore, this model can be used when there is not enough data on viscosity.

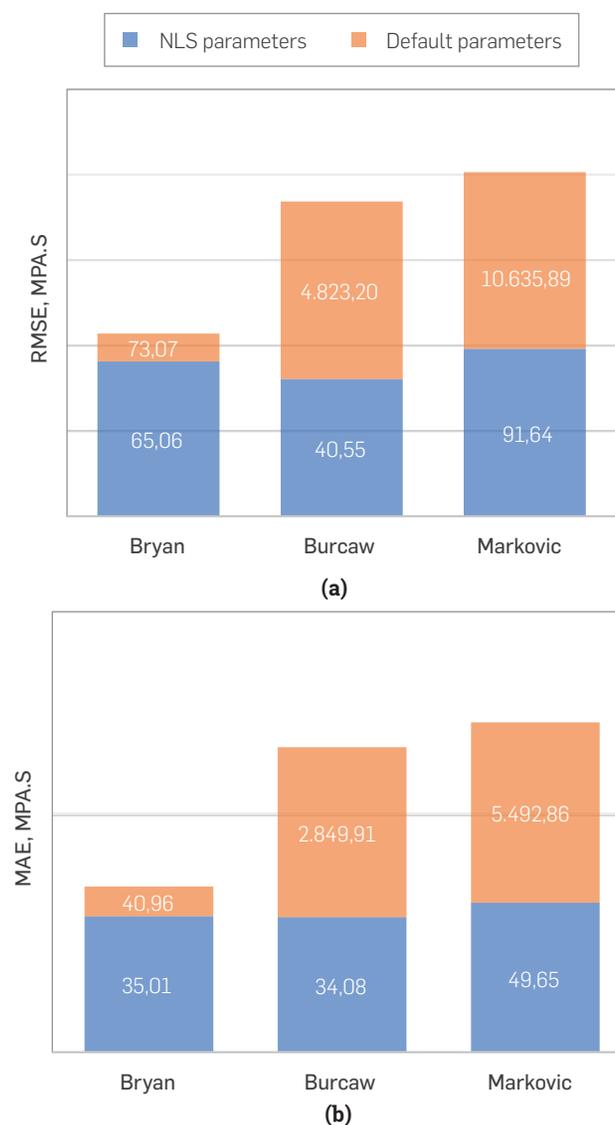
## DENSITY ESTIMATION BY NMR

The correlation proposed by Wen et al (2005) was used for density estimation. The Wen correlation shows an inversely proportional relationship between the NMR parameters ( $IA$  and  $T_{2gm}$ ) and density as per equation 6. The constants  $A$  and  $B$  were chosen from the values listed in **Table 4**. The constants selection was based on the lowest percentage of relative error ( $\epsilon$ ).

$$\rho_{\text{mixture}} = \frac{A}{(IA * T_{2gm})^B} \quad (6)$$



**Figure 6.** Rheological viscosities compared to NMR viscosities of 7 samples. Solid black line (1:1) presents a perfect prediction for all models.



**Figure 7.** Compared (a), Root-MSE (b) and MAE of NMR model predictions for using three model configurations. Bryan (2003), Burcaw (2007) and Markovic (2020)

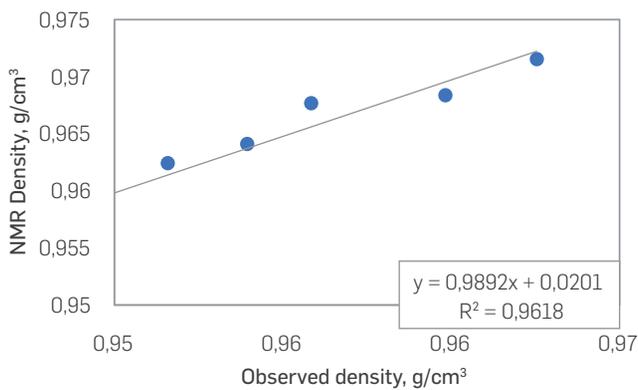
According to the tabulated data (Table 4), the lowest error percentages are reflected on the set of data number 2, where A=1.0373 and B=0.0117.

**Table 4.** Sensitivity for Density evaluation.

	ID1	ID2	ID3	ID4	ID5
A	1.0045	A 1.0356	A 1.0373	A 1.0286	A 1.0029
B	0.0114	B 0.0109	B 0.0117	B 0.012	B 0.0039
ε	3.9394	ε 0.6099	ε 1.0156	ε 2.0565	ε 1.2023

Figure 8 shows the graphical analysis of the results, where conventional density is compared with the value acquired by NMR. From the numerical study, a coefficient of determination of 0.96 and a linear relationship with a slope of 1.057 were obtained. These

values reflect the low percentage of error obtained and the high degree of precision of the Wen correlation.



**Figure 8.** Observed densities compared to NMR viscosities of 7 samples

### QUALITATIVE COMPARISON OF TECHNIQUES

The quantitative results prove that NMR is a reliable and accurate technique to evaluate oil viscosity and density based on mathematical models with acceptable errors, based on mathematical models. In addition, NMR is an alternative offering several qualitative advantages. **Table 5** shows a comparison between conventional techniques used in this investigation and the NMR technique.

The above comparative study shows the operational factors advantages that help overcome the issues related to common human errors and protocols when heavy oil is measured. Furthermore, density and viscosity models in literature have a wide range of application from light oils to extra heavy oils, with low prediction errors, provided that the parameters are correct. Moreover, the LF-NMR technique offers the possibility of conducting measurements, either at the lab or in situ, with borehole logging tools.

## CONCLUSIONS

This study evaluated and adjusted some mathematical models to estimate the viscosity and density of a Colombian heavy oil through LF-NMR. The best option to represent the viscosity was the Burcaw model, but only after the NLS regression, with RMSE and MAE values of 40.55 cP and 34.08 cP, respectively. On the other hand, the Wen correlation was preferred to determine density with a relative error of less than 1%, while the determination coefficient was 0.96.

Bryans model is a good option when there is not enough data available on viscosity to determine the fitting parameters through NLS regression. Because those found in the literature showed a good fit with the properties of Colombian heavy oil and the NMR equipment specifications. In addition, the acquired RMSE and MAE were slightly higher than the Burcaw model.

The comparison of both measurement techniques shows that low-field NMR is better than the conventional technique, as this technique helps overcome the issues to determine viscosity

**Table 5.** Qualitative comparison between measurements techniques.

Parameters	Conventional technique (Stabinger 3001 viscometer)	RMN technique
Test execution time	Longer sample heating time (30 minutes).	Sample preheating time less than 10 minutes.
	Time intervals lost during cleaning of the measurement cell after each run.	There are no missed time intervals between runs.
Sample volume required	30mL for dilutions.	Maximum 6mL per sample.
	150mL for the crude base.	
Equipment cleaning	It requires two solvent displacements plus a Nitrogen displacement and a measurement to verify that the cell was dry before starting the next run.	Not required, as the liquid samples do not come into direct contact with the equipment.
Measurable properties	Dynamic Viscosity Kinematic viscosity Density API	Dynamic Viscosity Density Kinematic viscosity API Molecular weight Sulfur content Total Acid Number Water content Aromatic Content Refractive index
Recovery of the sample	The sample changes its original properties when displaced with the cleaning fluid.	The samples are completely recovered.
Versatility	Handling a very viscous fluid with syringes tends to be a quite tedious and risky process, due to the difficulty of inserting the fluid into the syringe.	It is easier to handle the viscous fluids, as samples are processed in test tubes.
Costs per number of samples in this research	Total value Viscosity: \$583 USD	Total value (Viscosity and Density) \$260 USD
	Total value density: \$224 USD	
Repeatability of measurement	The process is longer, as it requires the displacement of 1mL more sample in each iteration; if at the end the values of the measured property are not coherent with each other, the whole process must be repeated from the washing and drying of the cell.	It is not necessary to change the volume of the initial sample and the repeatability's can be done continuously without having to remove the sample.

and density in heavy oil. It is worth to note that it offers multiple advantages as to operational and measurements factors, such as wide range for accurate density and viscosity measurement, a

shorter test execution time, minimum required sample volumes with 100% recovery, and no need for tedious cleaning procedures between measurements.

## ACKNOWLEDGEMENTS

The authors thank the Agencia Nacional de Hidrocarburos de Colombia (ANH), Ecopetrol S.A, Minciencias and Grupo de investigación Recobro Mejorado de Universidad Industrial de Santander for supporting this research work through Project number 56937: Evaluation of the use of flue gas in the cyclical injection of steam as an improved recovery method, in fields of the middle Magdalena region in Colombia.

## REFERENCES

- [1] Muhammad, A. & R. B. D. V. Azeredo, (2014). 1H NMR spectroscopy and low-field relaxometry for predicting viscosity and API gravity of Brazilian crude oils - A comparative study, *Fuel*, 130, 126-134. <https://doi.org/10.1016/j.fuel.2014.04.026>
- [2] Albuwarej, H., Felix, J., Taylor, S., Badry, R., Bremner, C., Brough, B., & West, C. (2006). La importancia del petróleo pesado. *Oilfield review*, 18(2), 38-58.
- [3] Butler, R., (1991). *Thermal Recovery of Oil and Bitumen*. United States.
- [4] Barbosa, L. L., Montes, L. F., Kock, F. V., Morgan, V. G., Souza, A., Song, Y. Q., & Castro, E. R. (2017). Relative hydrogen index as a fast method for the simultaneous determination of physicochemical properties of petroleum fractions. *Fuel*, 210, 41-48. <https://doi.org/10.1016/j.fuel.2017.08.057>
- [5] Miller, K. A., Nelson, L. A., & Almond, R. M. (2006). Should you trust your heavy oil viscosity measurement?. *Journal of Canadian Petroleum Technology*, 45(04), 42-48. <https://doi.org/10.2118/06-04-02>
- [6] Montes, L. F., Oliveira, E. C., Neto, Á. C., Menezes, S. M., Castro, E. R., & Barbosa, L. L. (2019). Low-field NMR: A new alternative to determine the aromatic content of petroleum distillates. *Fuel*, 239, 413-420. <https://doi.org/10.1016/j.fuel.2018.11.024>
- [7] Wen, Y., Bryan, J., & Kantzas, A. (2005). Evaluation of bitumen-solvent properties using low field NMR. *Journal of Canadian Petroleum Technology*, 44(04), 22-28. <https://doi.org/10.2118/05-04-02>
- [8] Markovic, S., Bryan, J. L., Turakhanov, A., Cheremisin, A., Mehta, S. A., & Kantzas, A., (2020). In-situ heavy oil viscosity prediction at high temperatures using low-field NMR relaxometry and nonlinear least squares, *Fuel*, 260(October 2019), 116328. <https://doi.org/10.1016/j.fuel.2019.116328>
- [9] Burcaw, L., Kleinberg, R., Bryan, J., Kantzas, A., Cheng, Y., Kharrat, A., & Badry, R. (2008, May). Improved methods for estimating the viscosity of heavy oils from magnetic resonance data. In *SPWLA 49th Annual Logging Symposium*. OnePetro. Austin, Texas.
- [10] Bryan, J., D. Moon, & A. Kantzas, (2005). In situ viscosity of oil sands using low field NMR, *Journal of Canadian Petroleum Technology*, 44(9), 23-29. <https://doi.org/10.2118/05-09-02>
- [11] Bryan, J., Kantzas, A., & Bellehumeur, C. (2005). Oil-viscosity predictions from low-field NMR measurements. *SPE Reservoir Evaluation & Engineering*, 8(01), 44-52. <https://doi.org/10.2118/89070-PA>
- [12] Morgan, V. G., Barbosa, L. L., Lacerda Jr, V., & Vinicius Ribeiro de Castro, E. (2014). Evaluation of the

physicochemical properties of the postsalt crude oil for low-field NMR. *Industrial & Engineering Chemistry Research*, 53(21), 8881-8889. <https://doi.org/10.1021/ie500761v>

[13] Barbosa, L. L., Sad, C. M., Morgan, V. G., Figueiras, P. R., & Castro, E. R. (2016). Application of low field NMR as an alternative technique to quantification of total acid number and sulphur content in petroleum from Brazilian reservoirs. *Fuel*, 176, 146-152. <https://doi.org/10.1016/j.fuel.2016.02.085>

[14] Sandoval-Martínez, M. I. & S. F. Muñoz-Navarro, (2019). Laboratory study of cyclic liquid solvent injection process for heavy oil recovery through computed tomography, *DYNA*, 86(210), 81-90. <https://doi.org/10.15446/dyna.v86n210.74983>

[15] Nunes, L. M., Cobra, P. F., Cabeça, L. F., Barbosa, L. L., & Colnago, L. A. (2012). In situ quantification of Cu (II) during an electrodeposition reaction using time-domain NMR relaxometry. *Analytical chemistry*, 84(15), 6351-6354. <https://doi.org/10.1021/ac3012889>

[16] Coates, G. R., Xiao, L., & Prammer, M. G. (1999). *NMR logging: principles and applications* (Vol. 234). Houston: Haliburton Energy Services.

[17] Constantino, A. F., Cubides-Román, D. C., dos Santos, R. B., Queiroz Jr, L. H., Colnago, L. A., Neto, Á. C., & Lacerda Jr, V. (2019). Determination of physicochemical properties of biodiesel and blends using low-field NMR and multivariate calibration. *Fuel*, 237, 745-752. <https://doi.org/10.1016/j.fuel.2018.10.045>

[18] Sandor, M., Cheng, Y., & Chen, S. (2016). Improved correlations for heavy-oil viscosity prediction with NMR. *Journal of Petroleum Science and Engineering*, 147, 416-426. <https://doi.org/10.1016/j.petrol.2016.09.004>

[19] Curtis, C., A. Guzmán-garcía, C. Huggins, L. Knauer, M. Minner, and H. Rough, (2003). Yacimientos de petróleo pesado, *Oilfield Review*, 12(6), 32-55.

[20] ASTM International. (2014). *Standard test method for dynamic viscosity and density of liquids by Stabinger viscometer (and the calculation of kinematic viscosity)*. ASTM D7042 - 21.

[21] Bryan, J., Kantzas, A., & Mirotnich, K. (2003). Viscosity determination of heavy oil and bitumen using NMR relaxometry. *Journal of Canadian Petroleum Technology*, 42(07), 29-34. <https://doi.org/10.2118/03-07-02>

## AUTHOR

### Maria Isabel Sandoval Martinez

Affiliation: Universidad Industrial de Santander, Colombia  
ORCID: 0000-0002-4540-0273  
e-mail: maria.sandoval@correo.uis.edu.co

### Herin Valderrama

Affiliation: Universidad Industrial de Santander, Colombia  
ORCID: 0000-0001-6496-3402  
e-mail: herin.valderrama@correo.uis.edu.co

### Miranda Sanchez

Affiliation: Universidad Industrial de Santander, Colombia  
ORCID: 0000-0001-5286-0393  
e-mail: miranda.sanchez@correo.uis.edu.co

### Daniel Molina Velasco

Affiliation: Universidad Industrial de Santander, Colombia  
ORCID: <https://orcid.org/0000-0002-4540-0273>  
e-mail: dmolina@uis.edu.co

### Samuel Fernando Muñoz

Affiliation: Universidad Industrial de Santander  
ORCID: 0000-0003-2814-3807  
e-mail: samuel@uis.edu.co

