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Development of an integrated RFID-IC technology for on-line viscosity measurements in enhanced oil recovery processes

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Abstract

This paper deals with on line viscosity measurements using integrated circuit technology, and is building on a previous paper on the use radio frequency identifier (RFID) technology for determining dielectric coefficients. It is asserted that the progress in RFID technology and integrated circuits, in particular in micro–electro–mechanical system (MEMS) makes it possible to combine them to perform physico-chemical property measurements using devices on centimeter scale. It can even be expected that these devices can be made increasingly smaller. An important property of interest is the viscosity, in this specific case, for the use of Arabic gum in enhanced oil recovery. Arabic gum, is an environmentally acceptable natural product. Natural-polymer solutions 1000 [ppm] are more viscous and therefore more efficient oil displacement agents. They require less invested exergy than non-viscosified water to recover oil. However, polymers, in particular environmentally acceptable natural-polymers (e.g., Guar–Arabic gum) available in large quantities in India and Sudan, are susceptible to microbial degradation. It is therefore important to monitor its quality at the injection and production side for real-time quality control. Natural-polymers based on plant products are promising EOR agents. They may have a lower environmental footprint because of the biodegradability. To provide a proof of concept, we use a state of the art acoustic wave sensor (AWS), which can determine acoustic viscosities. It is asserted that RFID technology can be used to record the acoustic wave signal (SenGenuity vismart acoustic wave Sensor AWS) to determine the viscosity at some distance (meters) away from the measurement device. A calibration with solutions of known viscosity behavior (i.e., Glycerol) can be used to relate the acoustic viscosity to the dynamic viscosity. We can calibrate the acoustic wave sensor using Guar–Arabic gum solutions to measurements with the Anton Paar viscometer (MCR-302). For the glycerol solution we also compare to reported literature data. The Newtonian viscosity measurements of the Paar density meter, and the literature values agree within a few percent. These favorable comparisons, are an important step in developing a methodology that allows cutting edge RFID-IC technology for real-time non-contact monitoring of viscosity degradation.

Keywords RFID technology · Integrated circuit (IC) · Acoustic wave sensor (AWS) · Viscosity degradation · Enhanced oil Recovery (EOR) · Natural-polymer (Guar–Arabic gum) solution

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Introduction

It can be expected that the progress in development of RFID technology and integrated circuits (IC's), in particular micro–electro–mechanical system (MEMS) makes it possible to combine them to perform wireless physicochemical property measurements using devices on the centimeter scale. These devices can be made increasingly smaller. An important property of interest is the viscosity. Polymer solutions around 1000 [ppm] are more viscous and therefore more efficient and require less energy or invested exergy than water to recover oil (Hassan and Bruining et al. 2018) thanks to faster recovery avoiding an ERoEI below one, i.e., low exergy return on high exergy investment, which frequently occurs towards the end of a recovery process. It is expected that the opportunities for EOR-polymer (polymer-based enhanced oil recovery) grow in the future (Forst and Sullivan 2012) avoiding an exergy return on exergy investment or ERoEI (recovered exergy divided by invested exergy) below one at the end of the project, as obtained with polymer free water injection. However, cost and environmental impact require a ERoEI well above one. Natural polymers based on plant products (Avwioroko et al. 2014) can be an alternative for synthetic polymers. In particular they have a lower environmental footprint because of their biodegradability (Hindi et al. 2017a, b). Polymers, in particular natural-polymers (e.g., Guar–Arabic gum) are susceptible to microbial degradation. It is therefore important to monitor its quality at the injection and production side for real-time quality control. One candidate polymer applicable in enhanced oil recovery is Guar–Arabic gum, which is available in large quantities in India and Sudan. In a separate contribution, it's showed with an exergy analysis that the use of Guar–Arabic gum leads to more efficient oil recovery, which requires less exergy for its production (Hassan and Bruining et al. 2018). In recent years, the combination of RFID technology with sensors has been used in applications to measure a wide range of environmental parameters including temperature (Opasjumruskit et al. 2006; Shenghua and Nanjian 2007; Vaz et al. 2010; Law et al. 2010; Virtanen et al. 2011), pressure (DeHennis and Wise 2002; Mori et al. 2004; Beriain et al. 2012), humidity (Jia et al. 2008; Virtanen et al. 2010, 2011; Amin et al. 2014) and chemical compositions (Potyrailo et al. 2012; Fiddes and Yan 2013). RFID tags have benefited from recent innovative research. Novak in his thesis Novak (2009) describes the use of the RFID tag as chemical sensor for trace substances. Ong et al. (2001) show that RFID technology can monitor the real and imaginary part of the dielectric coefficient of the medium surrounding the tag. Grimes et al. (2002) give an overview of sensors based on remote resonance frequency detection, which makes it possible to measure a variety of physical parameters. Only very recently the possibility of using RFID technology for determining dielectric coefficients, has been completely worked out by Hassan and Bruining Hassan et al. (2017). Humberto Lobato-Morales and his coauthors (Lobato-Morales et al. 2011, 2013) use a substrate-integrated-waveguide (SIW) resonant cavity and a tunnel sensor allowing the determination of the complex permittivity. The complex dielectric coefficient depends on the frequency; measurements at various frequencies therefore expand the capability using RFID's for measuring quantities that depend on more than two parameters (Warnagiris 2000). The paper of Karappuswami and his coauthors. Karuppuswami et al. (2016) is recently published and describes different sensor designs for measurement of dielectric properties via the response functions under far field conditions. The paper reports possible applications to fluid compositions, i.e., isopropyl alcohol–water and methanol–water mixtures. Karappuswami's research, which has been carried out in parallel with our research shows some overlap with the results described in this paper. Bonnier et al. (2013), present the development of an in line viscometer that can measure the viscosity at low shear rate in the field. The equipment consists of a pump that circulates the solution through a tube of given length and diameter. The pressure drop is measured, which can be used based on calibration data to determine the viscosity in line. Miller et al. (2011) describe a "Tuning Fork Instrument", which is capable of in line measurement of the density and viscosity of drilling fluids at 10-s intervals, but point out that the development is still at the early stage in particular as to the analysis of the readings. The advantage of using sensors is in their compactness, which facilitates its deployment at remote locations. The new aspect described in this paper is that it makes the applicability plausible of (relatively) small acoustic wave sensors (AWS) for real-time viscosity measurement, in combination with cutting edge wireless RFID technology to allow wireless and battery-less real-time monitoring operation of injected and production fluids (i.e., environmentally acceptable natural-polymer solutions) during enhanced oil recovery (EOR) processes. The advantage of using these sensors lies in its small size, wireless communication and its expected developments for using ever smaller size sensors and its expected development to affordable extensions as to fluids (i.e., Guar–Arabic gum) composition measurement. The organization of the paper is as follows: in second section, we describe the state of the art SeGenuity ViSmart℗ acoustic wave viscosity sensor (AWS), which is a solid-state viscometer based on bulk acoustic wave (BAW) technology. Third section describes how to deduce the so-called acoustic viscosity and the density using the calibration curve developed by "SeGenuity ViSmart". The

calibration curve transforms the acoustic viscosity to the dynamic viscosity. The thus measured viscosity is compared to literature values of glycerol (calibration fluid) viscosity. After an interpolation step, the measured dynamic viscosity only differs by few percent from the literature data of the viscosity of glycerol. Fouth section shows the results of measurement of the sensor of the polymer solutions. The viscosity of the polymer solution is compared to the viscosity measured with the Anton Paar viscometer (MCR). A difference of only a few percent is obtained. We end with some conclusions in final section.

Design and methods

We combine a state of the art Radio Frequency Identification using the RFID CISC Xplorer200, and MEMS technology using the SenGenuity Vismart acoustic wave Sensor AWS set-ups. The CISC RFID Xplorer-200 is a state of the art UHF (ultra high frequency) RFID system that consists of a reader (interrogator), which is connected to two circular patch antennae (transmitting and receiving) and a tag (transponder) (see Fig. 1). As the system has a separate transmitting RHCP or right-hand circularly polarized antenna and receiving LHCP or left-hand circularly polarized antenna (clockwise rotation of the electromagnetic wave) it is possible to transmit and receive signals simultaneously called

full-duplex radio (Dobkin and Wandinger 2005; Dobkin and Weigand 2006; Want 2006; Nikitin and Rao 2008; Novak 2009; Pursula et al. 2007; Dobkin 2012; Fiddes and Yan 2013). The Xplorer-200 allows to determine the scatter parameters as function of frequency and dielectric coefficients, and thus able to determine the dielectric permittivity of the medium surrounding the RFID tag (Hassan et al. 2017; Hassan 2016). The Xplorer-200 allows to connect to the Acoustic Wave Sensor AWS (MEMS) and transfer the data via an arduino-box from the (read/ write) tag to the receiving antenna (see Fig. 1).

The idea here is to use a rewrite RFID tag, which is able to store information from an acoustic wave sensor and uses wireless transfer to send it to the RFID-reader. The rewrite RFID tag is able to modulate the backscattered signal, which can then be separately amplified. Such a procedure makes it possible to read measurements, e.g., viscosity, at distances of up to 20 meters without using wires. New technologies, such as the Internet of Things (IoT) are expected to allow even longer distance data transmission, which would allow field operation, but currently the focus of interest is on RFID technology. Here we confine ourselves to the operation of the SenGenuity Vismart acoustic wave sensor (AWS). Such a sensor determines the acoustic properties of the environment surrounding the sensor, from which properties such as the density and viscosity can be inferred. The operating principles are based on bulk acoustic wave (BAW) technology
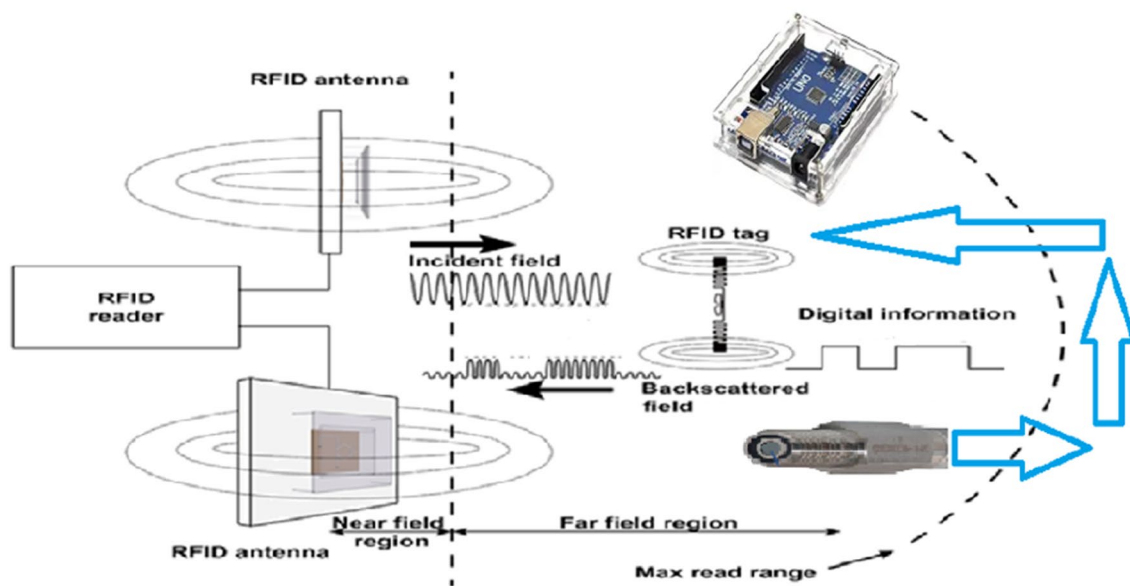
Fig. 1 RFID-IC communication system: the CISC RFID Xplorer-200 is a state of the art UHF RFID system that consists of a reader (interrogator), which is connected to two circular patch antennae, and the read write tag (transponder). The tag is able to modulate the backscattered signal, which can then be separately amplified. The tag-reader communication process is always initiated by the reader emitting antenna (RHCP), the (read write) tag can modulate the signal before transmitting it back to the receiver antenna (LHCP); as the system has separate transmitting and receiving antennae it is possible to transmit and receive signals simultaneously (full-duplex radio). The Xplorer-200 allows to connect with the acoustic wave sensor AWS (MEMS) and transfer the data via an arduino-box from the (read/ write) tag to the receiving antenna

(Vellekoop 1998; Gardner et al. 2001; Setter 2005). The X-tal in the sensor is a piezoelectric substrate sensing element, which is excited by a high-frequency oscillator and operates in the thickness shear mode (TSM). In this mode, shear displacement occurs at the surface of the piezoelectric crystal (see Fig. 2). When a TSM-BAW device is placed in a liquid solution, a layer of fluid couples to the vibrating surface of the sensor and creates an acoustic wave in the surrounding fluid, which after transmission is received and back-transformed to an electric signal. The propagated velocity carries information on the fluid density and sound speed, whereas the attenuation carries information on the viscosity (Thompson et al. 1991; Ballantine et al. 1996; Vellekoop 1998; Drafts 2001). Using a thickness shear mode (TSM) resonator, the elastic properties of a polymer solution can be measured (Ballantine et al. 1996). We have not found any reference to measure shear rate dependence on acoustic wave sensors. We compare the acoustic viscosity measurements with the Anton Paar Rheometer (NCR-302). This is a laboratory rheometer that can measure viscoelastic properties of, e.g., environmentally acceptable polymer (Guar–Arabic gum) solutions. A complete description of the rheological behavior of polymer solution is well presented by the Carreau (1972) model (Carreau 1972; Chen and Bogue 1972; Agassant et al. 2017) i.e.,
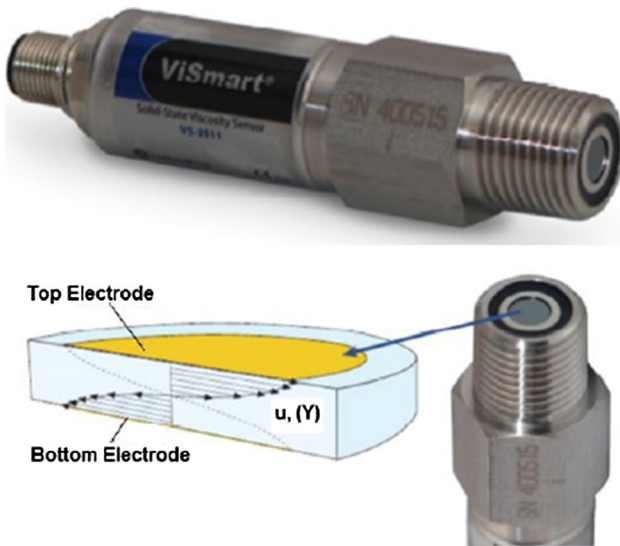
Fig. 2 Sengenuity acoustic wave sensor (AWS), ViSmart® VS-26xx series, based on Bulk Acoustic Wave technology with a viscosity range: 0–500 centistokes [cSt], Power supply: 5 [V], 35 [mA], Frequency: 5–2000 Hz. Crystal Sensor Surface showing the Thickness Shear Mode (TSM) of vibration. As shown in the bottom part of this figure 2, the displacement profile occurs through the entire thickness of the plate and is a maximum at the surfaces. Due to the fact that the displacement motion is parallel to the plate, the TSM keeps functioning in fluids, while protecting its surface, making it perfect for fluid sensing

$$\frac{\mu_w(c,s) - \mu_\infty(c)}{\mu_0(c) - \mu_\infty(c)} = \left(1 + \lambda(c)\dot{\gamma}(c,s)\right)^2\big)^{((n(c)-1/2)}, \qquad (1)$$

where (c) is the mass fraction, $\mu_0(c)$ is the zero shear-rate viscosity, $\mu_\infty(c) \approx 0$ is the infinite shear-rate viscosity, $\lambda(c)$ is a time constant, and $n(c)$ is the concentration dependent power law index. The shear rate $\dot{\gamma}$ in two phase flow can be written as (see Sorbie et al. 1987; Sorbie 2013, pp 176)

$$\dot{\gamma}(c,s) = C\left(\frac{3n(c) + 1}{4n(c)}\right)^{n(c)/(n(c)-1)} \frac{u}{\sqrt{kk_{rw}s\,\varphi}}, \qquad (2)$$

where $C = 6$ is a constant, $\mu_\infty(c) = 0$ and $n(c) = -15.366 * c + 0.4704$, $\lambda(c) = 0.0014 * \exp(199.97 * c)$. Moreover, s is the water saturation, c is the fractional concentration in mass per unit mass. Finally, u is the total Darcy velocity, $\varphi = 0.3$ is the porosity, $k = 10^{-12} m^2$ is the permeability and k_{rw} is the relative water permeability. We will assume that the relative permeability is given by

$$k_{rw} = \begin{cases} 0 & \text{for } 0 \le s \le s_{wc} \\ k_{rwe}\left(\frac{s - s_{wc}}{1 - s_{wc} - s_{or}}\right)^{n_w} & \text{for } s_{wc} < s \le 1 - s_{or}, \\ k_{rwe}\left(\frac{s_{or} - 1 + k_{rwe}}{s_{or}} + \frac{s(1 - k_{rwe})}{s_{or}}\right) & \text{for } 1 - s_{or} < s \le 1 \end{cases} \qquad (3)$$

where $k_{rwe} = 0.5$, $n_w = 2$, $s_{wc} = 0.2$ and $s_{or} = 0.3$.

Calibration of sensor with the Paar viscometer

For calibrating the sensor we use the data in Table 1. Table 1 shows in the first two columns the glycerol mixture used to make the solutions displayed in column 3 and 4. Column 5 expresses the concentration of glycerol in w/w %. Column-6 gives the viscosities of these solutions measured using the Anton-Paar viscometer (MCR-302). Column-7 shows the "acoustic viscosity" inferred from the measurements with the SenGenuity ViSmart® Acoustic Wave Sensor (AWS). Columns-8,9, 10 give the temperature, density and literature values of the glycerol solutions respectively. Column-11 and 12 give the difference between the measured glycerol viscosity with the Anton Paar Viscometer and the literature values and the error, i.e, the normalized difference between the measured Anton Paar viscosity (MCR-302) and the viscosity cited in the literature. The calibration is shown in terms of equations 1 and 2 used for the Carreau viscosity. The table summarizes our experimental data together with some literature data 1. The shear rate dependent viscosity of the Guar–Arabic gum that is manufactured in Sudan is measured using the Anton Paar "viscometer". The data in
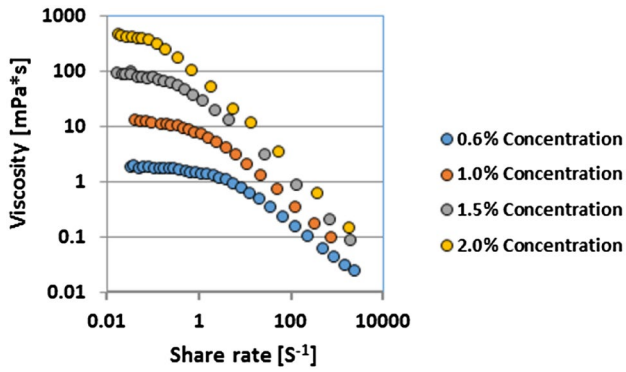
Fig. 3 The viscosity [mPa s] of Guar—Arabic gum as a function of the shear rate [s^{-1}] (see Eq. 2), which has been measured using the Anton Paar viscometer (MCR-302)
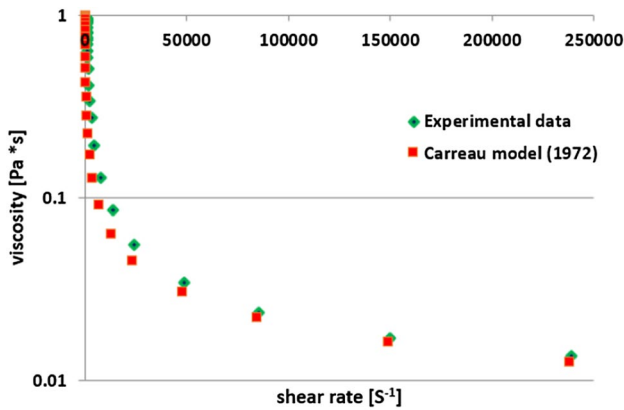

Fig. 4 A comparison between the rheological behavior of polymer solution by Carreau's model (1972) and experimental data

Fig. 3 is used to obtain the regression expressions of $n(c)$, and $\lambda(c)$ using the solver in EXCEL.

Results and discussion

Figure 4 shows the comparison between Carreau's model (Eq. 1), where the concentration dependent power law index $n(c)$ and a concentration dependent time constant $\lambda(c)$ have been used with the experimental data. The results show the same trend, but also a difference between measured and the regression results around a shear rate of 0–20000. Above a shear rate of 20000, there is good agreement. Figure 5 shows a comparison between the Anton Paar viscosity and the literature data on the viscosity of glycerol solutions. The agreement is excellent. It shows the applicability of the Anton-Paar viscometer for high precision measurement of polymer solutions. Figure 6 compares the viscosity measured with the Anton Paar Viscometer with the viscosity measured by the acoustic sensor. There is a difference between the values showing that an intermediate calibration step is necessary. After this calibration the interpolated data of the sensor shows excellent agreement with the data obtained with the Paar viscometer. It shows that a comparison in a work flow that uses the Anton Paar viscometer and the acoustic wave sensor is a promising method to validate the wireless Sen-Genuity Vismart for real-time measurements of the viscosity and thus for an on line quality control for polymer enhanced oil recovery. In addition such a work flow can help with a proof of concept of combining the acoustic wave sensor with RFID. Still the integration of RFID or alternatively the (Internet of Things, IoT) with sensor technology needs to be further elaborated.

Fig. 5 The concentration of the calibration fluid (Glycerol) as function of dynamic viscosities from Anton Paar viscometer (MCR-302) and literature
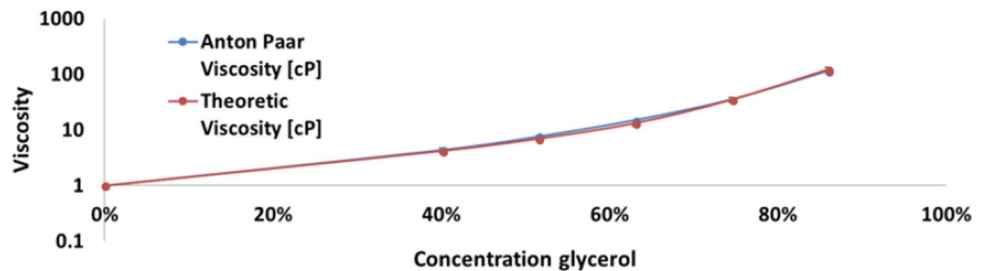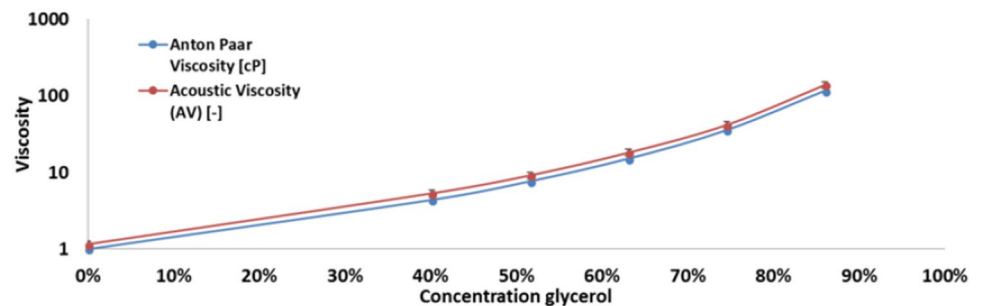

Fig. 6 The concentration of the calibration fluid (Glycerol) as function of acoustic viscosity (AV) and dynamic viscosities, which are measured by Sengenuity Acoustic Wave Sensor and Anton Paar viscometer (MCR-302) respectively

Table 1 Parameters of data calibration (*T* temperature, *Lit.* literature, *Diff* difference)

C3H8O3 86 w/w% (mL)	H2O w/w 0% (mL)	C3H8O3 w/w %	H2O w/w %	C3H8O3 (%)	Viscosity (mPa s)	Viscosity (AV)	T[C]	Density (g/cm³)	Lit. visc (mPa s)	Diff. (mPa s)	Error (%)
15	0	12.9	2.1	86	115.804	139.390	20	1.22	121.98	6.176	5
13	2	11.18	3.82	75	35.5154	41.783	20	1.19	34.94	0.575	2
11	4	9.46	5.54	63	15.0902	18.146	20	1.16	13.23	1.860	12
9	6	7.74	7.26	52	7.66225	9.1561	20	1.13	6.975	0.687	9
7	8	6.02	8.98	40	4.38143	5.3296	20	1.10	4.21	0.171	4
0	15	0	15	0	1	1.150	20	1.00	1.0	0	0

The Viscosity column shows the measurements with the Anton Paar viscometer (MCR-302) and the column denoted by (AV) shows the acoustic viscosity measured with the SenGenuity Vismart acoustic wave Sensor (AWS). It makes it possible to make a calibration curve between the acoustic viscosity and the viscosity obtained from the literature

Conclusions

(1) Guar–Arabic gum is an environmentally acceptable natural product, which is available in large quantities in India and Sudan; it can increases the viscosity of an aqueous solution to about 800 [mPa s] at concentrations of 2 w/w%, thus beneficial for enhanced oil recovery (EOR) processes.

(2) There is a difference between the glycerol acoustic viscosity values obtained with SenGenuity ViSmart® Acoustic Wave Sensor (AWS) and the shear viscosity obtained with the Anton Paar viscometer, showing that an intermediate calibration step is necessary. After this calibration is done, the interpolated data of the sensor shows excellent agreement with the data obtained with the Paar viscometer.

(3) A expected, the viscosity versus the shear rate measured with the Anton Paar viscometer follows Carreau's model.

(4) The optimal fitting requires a concentration dependent power law index $n(c) = -15.366 * c + 0.4704$ and a concentration dependent time constant $\lambda(c) = 0.0014 * \exp(199.97 * c)$. The optimal regression equations are obtained using the EXCEL solver to obtain the characteristic concentration dependent power index and the concentration dependent time constant, and using Eureqa ^{TM} to obtain the regression expressions. Eureqa ^{T}M does not require an a priori choice of the regression equation.

(5) Some preliminary acoustic viscosity data with Arabic gum without Guar, which has a low viscosifying effect have been obtained, but makes it plausible that the sensor can be used to monitor in situ polymer enhanced viscosities

(6) The integration of cutting edge RFID or alternatively the (Internet of Things, IoT) technology with Acoustic wave sensor (AWS) technology needs to be further optimized.

References

Agassant J.-F, Avenas P, Carreau PJ, Vergnes B, Vincent M (2017) Polymer processing: principles and modeling. Carl Hanser Verlag GmbH Co KG

Amin EM, Bhuiyan MS, Karmakar NC, Winther-Jensen B (2014) Development of a low cost printable chipless rfid humidity sensor. IEEE Sens J 14(1):140–149

Avwioroko J, Taiwo O, Mohammed I, Dala J, Olafuyi O, et al. (2014) A laboratory study of asp flooding on mixed wettability for heavy oil recovery using gum arabic as a polymer. In: Spe nigeria annual international conference and exhibition

Ballantine D Jr, White RM, Martin SJ, Ricco AJ, Zellers E, Frye G, Wohltjen H (1996) Acoustic wave sensors: theory, design and physico-chemical applications. Elsevier

Beriain A, Rebollo I, Fernandez I, Sevillano JF, Berenguer R (2012) A passive uhf rfid pressure sensor tag with a 7.27 bit and 5.47 pj capacitive sensor interface. In: Microwave symposium digest (mtt), 2012 ieee mtt-s international (1–3)

Bonnier J, Rivas C, Gathier F, Quillien B, Thomas A, et al. (2013) Inline viscosity monitoring of polymer solutions injected in chemical enhanced oil recovery processes. In: Spe enhanced oil recovery conference

Carreau PJ (1972) Rheological equations from molecular network theories. Trans Soc Rheol 16(1):99–127

Chen I-J, Bogue D (1972) Time-dependent stress in polymer melts and review of viscoelastic theory. Trans Soc Rheol 16(1):59–78

DeHennis A, Wise KD (2002) A double-sided single-chip wireless pressure sensor. In: The fifteenth IEEE international conference on micro electro mechanical systems, 2002, pp 252–255

Dobkin DM (2012) The rf in rfid: uhf rfid in practice. Newnes

Dobkin DM, Wandinger T (2005) A radio oriented introduction to radio frequency identification. RFID Tutorial High Freq Electron 46–54

Dobkin DM, Weigand SM (2006) Uhf rfid and tag antenna scattering part i: Experimental results-first in a two-part series on the use of radio frequency communications to identify physical objects in the commercial supply chain. Microwave J 49(5):170–191

Drafts B (2001) Acoustic wave technology sensors. IEEE Trans Microwave Theory Tech 49(4):795–802

Fiddes LK, Yan N (2013) Rfid tags for wireless electrochemical detection of volatile chemicals. Sensors Actuators B Chem 186:817–823

Gardner JW, Varadan VK, Awadelkarim OO (2001) Microsensors, mems, and smart devices, vol 1. Wiley Online Library

Grimes CA, Mungle CS, Zeng K, Jain MK, Dreschel WR, Paulose M, Ong KG (2002) Wireless magnetoelastic resonance sensors: a critical review. Sensors 2(7):294–313

Hassan A (2016) The use of rfid technology in solvent-enhanced imbibition experiments. LAP Lambert Academic Publishing. https://books.google.nl/books?id=2yUqvgAACAAJ

Hassan A, Bruining H, Musa T, Chahardowli M (2017) The use of rfid technology to measure the compositions of diethyl ether–oil–brine mixtures in enhanced imbibition experiments. J Pet Sci Eng 156:769–779

Hindi S, Albureikan M, Al-Ghamdi A, Alhummiany H, Al-Sharabi SM (2017) Effect of potassium dichromate on properties and biodegradation of gum arabic based bioplastic membranes. Nanosci Nanotechnol 4(2):49–58

Hindi S, Albureikan MO, Al-Ghamdi AA, Alhummiany H, Ansari MS (2017) Synthesis, characterization and biodegradation of gum arabic-based bioplastic membranes. Nanosci Nanotechnol 4(2):32–42

Jia Y, Heiß M, Fu Q, Gay NA (2008) A prototype rfid humidity sensor for built environment monitoring. In: International workshop on education technology and training, 2008. and 2008 international workshop on geoscience and remote sensing. ett and grs 2008, vol 2, pp 496–499

Karuppuswami S, Kaur A, Ghazali MIM, Chahal P (2016) Rfid compatible sensor tags for remote liquid sample interrogation. In: Electronic components and technology conference (ectc), 2016 ieee 66th, pp 2401–2407

Law MK, Bermak A, Luong HC (2010) A sub-μmw embedded cmos temperature sensor for rfid food monitoring application. IEEE J Solid State Circ 45(6):1246

Lobato-Morales H, Corona-Chávez A, Olvera-Cervantes JL (2013) Planar sensors for rfid wireless complex-dielectric-permittivity sensing of liquids. In: Microwave symposium digest (ims), 2013 ieee mtt-s international, pp 1–3

Lobato-Morales H, Murthy D, Corona-Chávez A, Olvera-Cervantes JL, Martínez-Brito J, Guerrero-Ojeda LG (2011) Permittivity measurements at microwave frequencies using epsilon-near-zero (enz) tunnel structure. IEEE Trans Microw Theory Tech 59(7):1863–1868

Miller A, Minton RC, Colquhoun RL, Ketchion M et al (2011) The continuous measurement and recording of drilling fluid density and viscosity. In: Spe/iadc drilling conference and exhibition

Mori T, Suemasu Y, Noguchi H, Sato T (2004) Multiple people tracking by integrating distributed floor pressure sensors and rfid system. In: 2004 ieee international conference on systems, man and cybernetics, vol 6, pp 5271–5278

Nikitin PV, Rao KS (2008) Antennas and propagation in uhf rfid systems. In: 2008 ieee international conference on Rfid, pp 277–288

Novak GD (2009) Rfid tags/planar inductors as chemical sensor platforms in liquid sensing applications (Unpublished doctoral dissertation). MARQUETTE UNIVERSITY

Ong KG, Grimes C, Robbins C, Singh R (2001) Design and application of a wireless, passive, resonant-circuit environmental monitoring sensor. Sens Actuators A Phys 93(1):33–43

Opasjumruskit K, Thanthipwan T, Sathusen O, Sirinamarattana P, Gadmanee P, Pootarapan E, Thamsirianunt M (2006) Self-powered wireless temperature sensors exploit rfid technology. IEEE Pervas Comput 5(1):54–61

Potyrailo RA, Nagraj N, Tang Z, Mondello FJ, Surman C, Morris W (2012) Battery-free radio frequency identification (rfid) sensors for food quality and safety. J Agric Food Chem 60(35):8535–8543

Pursula P, Hirvonen M, Jaakkola K, Varpula T (2007) Antenna effective aperture measurement with backscattering modulation. IEEE Trans Antennas Propag 55(10):2836–2843

Setter N (2005) Electroceramic-based MEMS Electroceramic-based mems. Springer, Berlin

Shenghua Z, Nanjian W (2007) A novel ultra low power temperature sensor for uhf rfid tag chip. In: Solid-state circuits conference, 2007. asscc'07. ieee asian, pp 464–467

Sorbie K, Parker A, Clifford P (1987) Experimental and theoretical study of polymer flow in porous media. SPE Reserv Eng 2(03):281–304

Sorbie KS (2013) Polymer-improved oil recovery. Springer, Berlin

Thompson M, Kipling AL, Duncan-Hewitt WC, Rajaković LV, Čavić-Vlasak BA (1991) Thickness-shear-mode acoustic wave sensors in the liquid phase. a review. Analyst 116(9): 881–890

Vaz A, Ubarretxena A, Zalbide I, Pardo D, Solar H, Garcia-Alonso A, Berenguer R (2010) Full passive uhf tag with a temperature sensor suitable for human body temperature monitoring. IEEE Trans Circ Syst II Express Briefs 57(2):95–99

Vellekoop MJ (1998) Acoustic wave sensors and their technology. Ultrasonics 36(1–5):7–14

Virtanen J, Ukkonen L, Bjorninen T, Elsherbeni AZ, Sydänheimo L (2011) Inkjet-printed humidity sensor for passive uhf rfid systems. IEEE Trans Instrum Meas 60(8):2768–2777

Virtanen J, Ukkonen L, Björninen T, Sydänheimo L (2010) Printed humidity sensor for uhf rfid systems. In: Sensors applications symposium (sas), 2010 ieee, pp 269–272

Virtanen J, Ukkonen L, Björninen T, Sydänheimo L, Elsherbeni AZ (2011) Temperature sensor tag for passive uhf rfid systems. In: Sensors applications symposium (sas), 2011 ieee, pp 312–317

Want R (2006) An introduction to RFID technology: an introduction to rfid technology. IEEE Pervas Comput 5(1):25–33

Warnagiris TJ (2000) Liquid sensing at radio frequencies Liquid sensing at radio frequencies. Microwave J Euroglobal edition- 43(9):140–151