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Thermo-Acoustic Water Analyzer in Hydrocarbon Emulsions with Kalman Filter

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Abstract: Problem statement: Water detection in hydrocarbon emulsions represents a serious challenge in petroleum production industry. The elemenation of measurment noises is also desired. **Approach:** In this study, a systematic and an applicable method of water detection in hydrocarbon emulsion is achieved using thermoacoustic effect. A Kalman filter is applied to correct measurement errors and to improve accuracy. **Results:** The study focused on sensing the presence of water in kerosene using the established correlation between the content of hydrocarbon emulsion and the characteristics of the acoustic wave generated by inundation of a heated rod in the emulsion. The implemented filteration enhanced the peromance of the measurment system. **Conclusion:** This approach was tested experimentally and showed that the produced acoustic signal can be utilized as an informative parameter in quality control schemes of petrochemical oil products.

Key words: Thermoacoustic technology, water detection, petrochemical oil products, Kalman filter

INTRODUCTION

Thermo Acoustics (TA) refers to the physical phenomenon that heat can generate and amplify a sound wave and vice versa. The generation of a stress wave or sound is produced as a consequence of thermal expansion induced by temperature variation. Thermoacoustic technology uses high amplitude acoustic waves in pressurized gas to transfer heat, it also uses temperature difference to induce sound. Recent development and applications of TA systems are mainly based on the study of (Rott, 1969; 1980), (Swift, 1988), who developed linear thermoacoustic models. Temperature oscillations associated with acoustic waves in fluids allowed the construction of thermoacoustic engines and refrigerators through contact of fluid with surfaces having high heat capacity. Recently, researchers have focused on investigating the potential of utilizing thermoacoustic phenomena in sensing techniques (Ku *et al*., 2005; Pramanik *et al*., 2008). This study focuses on sensing the presence of water in oil using oscillatory heat exchange process to detect water content percentage in hydrocarbon fuel. This is achieved through acoustic wave generation by thermal excitation of small regions (Kino and Stearns, 1985). In this approach, the key factor contributing to acoustic wave generation is thermal expansion of material and its interaction with volume dilation associated with the acoustic field of receiving transducer.

Water detection in hydrocarbon emulsions: Detection of water content in oil products is a significant indicator of oil monitoring procedures as water in oil appears as a hydrocarbon emulsion. Although, several techniques are available to determine water level in hydrocarbon emulsions, they require laboratory equipments to provide accurate and reliable data. Therefore, these procedures are time consuming and not practical for field work, where instant measurement is crucial for management of effective processing.

A well established method for detecting water is using special pastes which alter color on contact with water (Iqbal *et al*., 2009), such as Kolor Kut modified water finding paste or VECOM water finding paste. In literature, one can find a range of efforts in detecting water contamination in gasoline, such as addition of methylen crystal (Guven and Gezgin, 2004), which turns emulsion blue if contaminations existed. Other work suggested detection of water in petroleum products by exposing oil to a substance which is chemically inert. This substance interacts with water to produce gas and the produced gas is measured by displacement of liquid from a closed vessel (Pedersen, 1978). The main drawbacks of this method are complexity and large measurement duration of approximately 3 meter.

Recently, acoustic research brought much attention to the fields of transducers and devices, which are the basic blocks of laboratory analyzers and measurement

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systems, such as: gas detectors (Younes, 2003) and temperature detectors (Alia and Al-Mograbi, 2007). The design of these detectors is based on the measurement of one or more parameters of acoustical characteristics in the domain of interest. Researchers have proposed velocity measurement of sound transmission in the fluid stream (US. Pat. No 4,236,406 and 4,080,837), however, the presence of gas in the stream can affect the measurement. In (U.S. patent No 4,573,346), the volume of water and oil in a stream was determined by consecutive measurement of upstream and downstream sound velocity using a pair of sonic flow meters (Zachrias, 1986), the resulting data will yield both flow rate and concentration of water in oil. Such a technique is relatively complicated and expensive.

A common method of water detection in petroleum industry is chromatography (Senn and Johnson, 1987; Acqua *et al*., 1975). Chromatographs are used to give quantitative and qualitative analysis of gases and vapors. However, it is impractical to maintain a chromatograph in non laboratorial zone. Gas chromatography is mainly used at early stages of quality control procedures in oil production, whereas the content of oil products may be contaminated as a result of oil storage or during transportation.

Therefore, this research is directed towards the investigation and utilization of a practical method for detecting, monitoring and measuring of water content in hydrocarbon emulsion and/or detection of oil in water.

Thermoacoustic detector: The operation of this detector is based on the fact that when heat diffuses in the emulsion by the heated rod, a mechanical stress arises, which causes the generation of the acoustic wave whose properties are determined by the characteristics of the medium, i.e. the emulsion thermal expansion forms the acoustic signal (Srivastava *et al*., 2006).

The heat source determines the Pressure (P) in an acoustically homogeneous medium at time t and position r as (Guo *et al*., 2007; Lou and Xing, 2010):

$$\nabla^2 p(r,t) - \frac{1}{v_s^2}\frac{\partial^2}{\partial t^2}p(r,t) = -\frac{\beta}{C_p}\frac{\partial}{\partial t}Q(r,t) \quad (1)$$

where, β is thermal coefficient of volume expansion, v_s is speed of sound, C_p is the specific heat capacity at constant pressure and Q is thermal energy per unit time and unit volume.

Assuming the change in volume is negligible, the solution of Eq. 1 under thermal and stress confinement, subject to zero-initial conditions (Xu *et al*., 2004):

$$p = \frac{\beta v_s^2}{C_p} Qabs = \Gamma Q_{abs} \quad (2)$$

where, Q_{abs} is the absorbed energy by unit volume of the emulsion. The expression of $\beta v_s^{2/}C_p$ represents the Grüneisen parameter (Γ) is a dimensionless factor that is proportional to the fraction of thermal energy; converted into mechanical stress which is related to the thermal and bulk properties of the emulsion. Grüneisen parameter equals to 0.11 for water at 100°C and 0.15-0.2 for hydrocarbon liquids.

Equation 2 demonstrates that the thermoacoustic pressure P is dependent on emulsion characteristics, it varies based on the reaction to changes in emulsion composition including: β, Γ and Q_{abs} at constant temperature (Aktas *et al*., 2004; Toubal *et al*., 1999).

Therefore, the Grüneisen parameter determines the thermoacoustic-conversion efficiency in the emulsion, which is three times larger for water than gasoline (Ozoe *et al*., 1980). Thus, in practice, the measured acoustic pressure signal generated can be used to monitor the emulsion composition at constant-temperature environment.

MATERIALS AND METHODS

The proposed sensing method is based on the established correlation between the content of hydrocarbon emulsion and the parameters of generated acoustic wave resulted by inundation of a heated rod in the emulsion.

The system components of TA sensing apparatus are shown in Fig. 1. Initially, mixing of emulsion was done through consistent shaking. To validate suggested procedure, the mixture was tested in glass, plastic and stainless flasks. Flasks volumes were 1000 500, 400, 300, 200 and 100 mL. The temperature of inundated rod was 100 and 150°C. The mixture volumes were 100, 200 and 300 mL. The acoustic wave is retrieved using a sensitive hydrophone linked to a computer for signal processing.

In order to study the produced acoustic signal, the signal is analyzed using a customized program under CBuilder-5 environment, it continuously measures the frequency of generated sound signal. The measured frequency which is displayed on a chart recorder yields the desired information about water content in hydrocarbon emulsion.

Error correction using Kalman filtering: In Kalman filter, a linear and recursive estimator, the states of the system are defined to estimate system behavior. Also, a measurement model is defined to characterize the relationship between the state vector and any measurement. The state vector **x** of the system at time (k+1) are produced by Eq. 3 (Brown and Hwang, 1997):

$$x_{k+1} = \phi_k x_k + w_k \quad (3)$$

where, ϕ_κ is the state transition matrix. The noise w_k is a white Gaussian noise with zero mean and covariance Q_k. To apply Kalman filter in measurement correction procedure, the state vector is defined as the average acoustic peak with glass flask at 100°C, emulsion volumes: 100, 200, 300 mL. The state transition matrix ϕ_κ is an identity matrix of 3×3.

The process measurement is defined as Eq. 4:

$$z_k = H_k x_k + v_k \tag{4}$$

Where:

H_k = The measurement matrix and noise

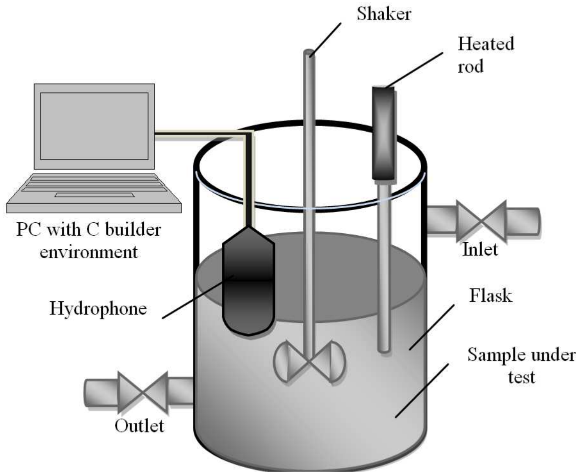

Fig. 1: The experimental set-up schematic for water content detection

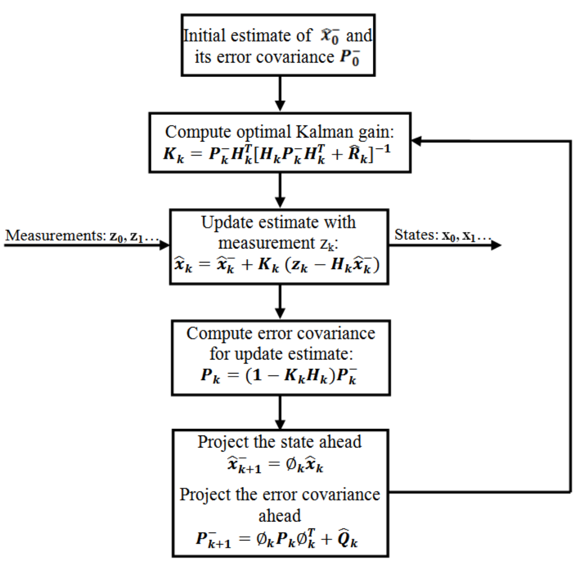

Fig. 2: Kalman filter procedure

v_k = Assumed to be Gaussian with covariance matrix R_k. v_k has zero cross-correlation with w_k

The measurement vector is vector of ones of 3×1.

The implementation of Kalman filter procedure is shown in Fig. 2, (Chui and Chen, 2009). The procedure is initiated by the assumption of x^-_0 and P^-_0: initial estimate of states and its error covariance respectively. The optimal Kalman gain K_k is utilized to achieve the update estimate of the measurements x_k and its error covariance P_k. The next state x^-_{k+1} and error covariance P^-_{k+1} are then calculated based on the current state estimate. For estimating of GPS receiver coordinates.

The filter accuracy is measured using 2DRMS (Twice Distance Root Mean Squared). The computation of *2DRMS* is attained by Eq. 5:

$$2DRMS = 2\sqrt{(\sigma_1^2 + \sigma_2^2)} \tag{5}$$

where, σ_1, σ_2 are the standard deviations of the measurements by Kalman filter.

RESULTS

To investigate the correlation between water content and acoustic wave frequencies, Fig. 3, the area of acoustic signal peaks (the peak of the basic harmonic) is estimated, this method is frequently implemented in chromatography (Felinger, 1998).

Samples are prepared in steady still conditions so that sound resulted by evaporation will not affect the measurements, also consistent temperature should be preserved throughout the procedure.

In order to evaluate the proposed technique and to investigate the relationship between composition and thermo acoustic pressure, multiple water-in-emulsion percentages are tested to estimate the average frequencies of acoustic peaks for different flask types and emulsion volumes as shown in Fig. 4-6.

The average frequency of the acoustic peaks is curve-fitted by a third order polynomial function. The main factors which may affect the generated sound signal are: flask material, heated-rod temperature and volume of mixture. It was found that the temperature variation has a significant impact on the area under the acoustic curve. As shown in Fig. 4, using different mixture volumes in the same flask has no significant effect on the peaks area of the acoustic wave.

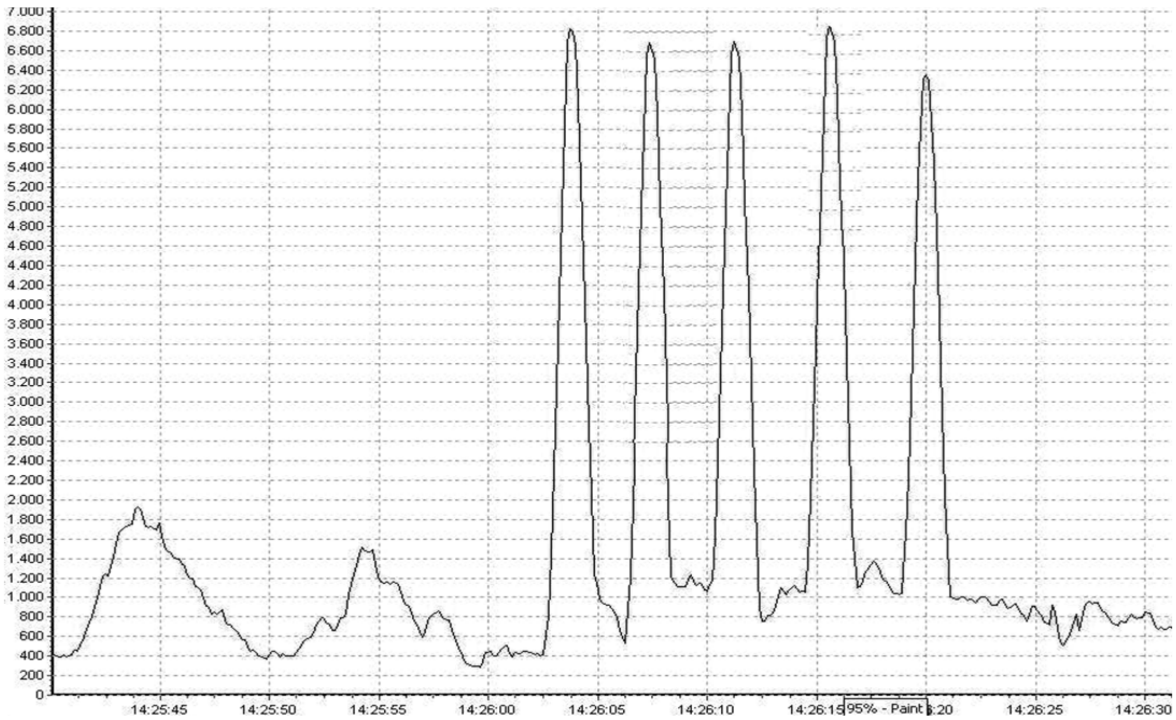

Fig. 3: Peaks of acoustic signal for plastic flask at 150°C, 100 mL, 95% kerosene

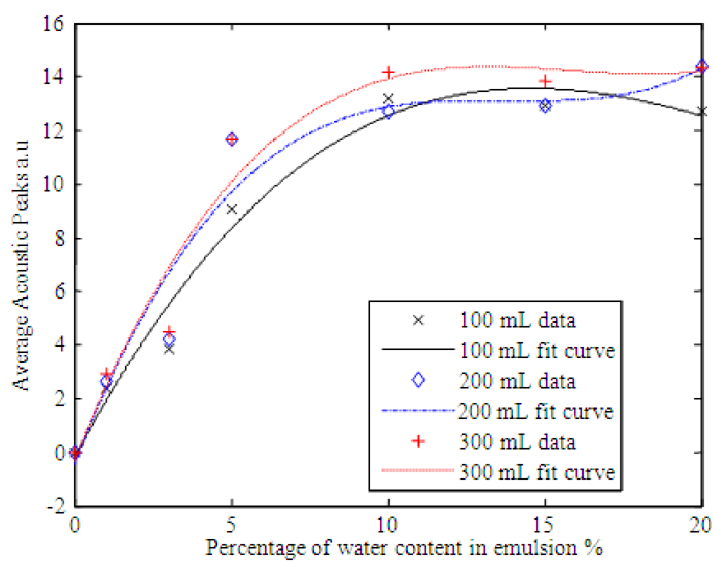

Fig. 4: Average frequencies of acoustic peaks with glass flask at 100°C, emulsion volumes: 100, 200, 300 mL

The flask material has a clear effect on peaks area of the sound signal. The type of flask material defines the behavior of produced acoustic signal which depends on the acoustic impedance Z (Pallas-Areny and Webster, 2001). Z is a characteristic parameter for each medium: $Z_{air} \approx 4.310^{-4}$ Pa. sm^{-1}, $Z_{water} \approx 1.5$ $Pa.sm^{-1}$, $Z_{steel} \approx 45$ $Pa.sm^{-1}$.

As shown in Fig. 6, using a stainless steel flask produces better consistent measurements for various emulsion compositions and flask sizes.

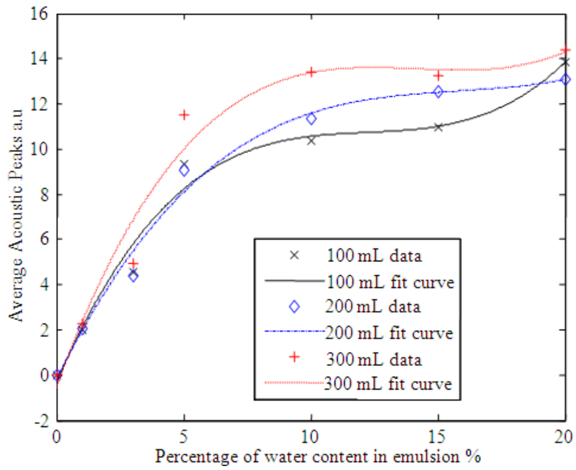

Fig. 5: Average frequencies of acoustic peaks with plastic flask at 100°C, emulsion volumes: 100, 200, 300 mL

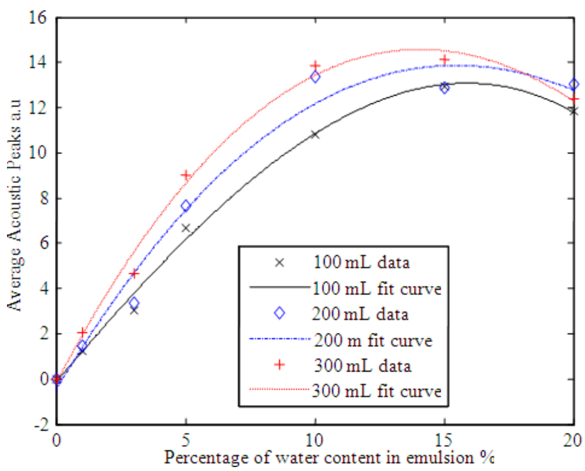

Fig. 6: Average frequencies of acoustic peaks with stainless steel flask at 100°C, emulsion volumes: 100, 200, 300 Ml

DISCUSSION

Based on these experimental results, this technique is recommended to detect water-in-oil with percentages of 10% or less. To study the effect of flask sizes on the acoustic signal, shown in Fig. 7, sizes 100, 200 mL and 300 mL were used in the procedure. As seen the flask size has no effect on the acoustic signal when water content is below 10% of the emulsion.

Furthermore, several experimental tests were performed to study the influence of using different materials for the flask. As shown in Fig. 8, the acoustic signal is proportional to the water content under 10% of emulsion with no significant effect of material used.

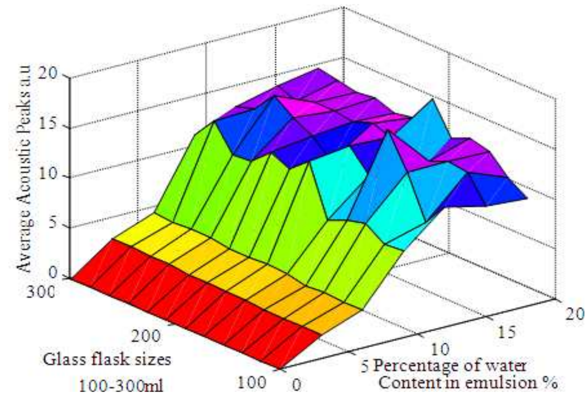

Fig. 7: Average acoustic peaks for various glass flask sizes 100-300 mL, with different percentages of water content in the emulsion

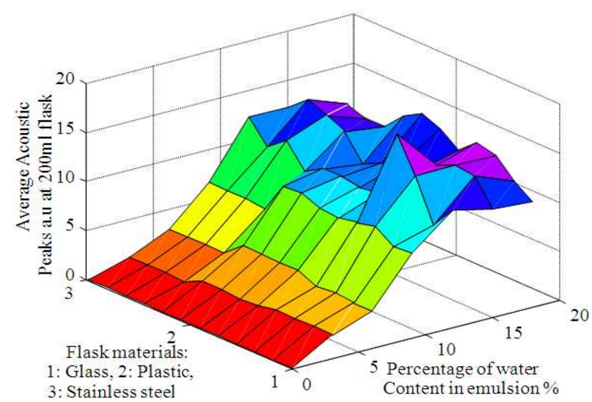

Fig. 8: Average acoustic peaks for different Flask materials: 1: glass, 2: plastic, 3: stainless steel, with different percentages of water content in the emulsion

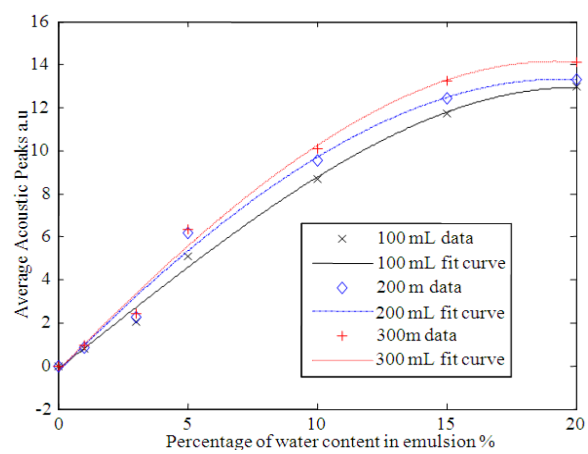

Fig. 9: Average frequencies of acoustic peaks with glass flask at 100°C, emulsion volumes: 100, 200, 300 mL with Kalman filter

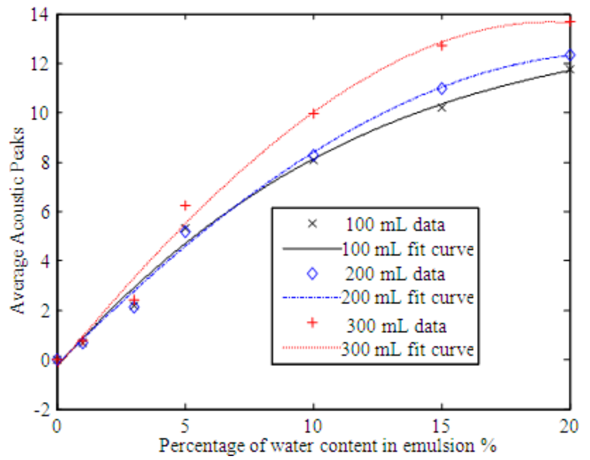

Fig. 10: Average frequencies of acoustic peaks with plastic flask at 100°C, emulsion volumes: 100, 200, 300 mL with Kalman filter

The data filtration using Kalman filter was performed. The results showed a remarkable enhancement of the measurement accuracy. The average frequencies of acoustic peaks with glass and plastic flasks at 100°C, emulsion volumes: 100, 200, 300 mL with Kalman filter are shown in Fig. 9, 10 respectively.

The accomplished results were reliable and support the application of such system to the industrial applications. The calculated accuracy was more than 95% on average. The best detecting results are found with glass flasks with more than 97% accuracy.

Based upon these results, this experimental procedure, to use TA principle to detect the water content in hydrocarbon emulsion with Kalman filteration, established a practical method to monitor water-in-oil in industrial application.

CONCLUSION

A systematic method for detecting water content in hydrocarbon emulsion is proposed using the application of a TA-based technique. The experimental results revealed that the generated acoustic signal is related to the properties of the tested hydrocarbon emulsion. The tested thermo acoustic detector demonstrated a sufficient level of precision to sense water-in-oil content if less than 10%. To improve this accuracy, we implemented a Kalman filter which reduced the error percentage to 2-5%. This general approach can be utilized in different quality control tests.

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