Online estimation of wax deposition thickness in single-phase sub-sea pipelines based on acoustic chemometrics: A feasibility study

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Abstract

Wax deposition in sub-sea oil producing pipelines is a concern to the oil producing companies. The deposition of wax in pipelines can cause serious economic implications if not monitored and controlled. Several researchers have developed models and investigated the deposition of wax in crude oil pipelines. As of today, there is no *off the shelf* instrument available for reliable online estimation of the wax deposition thickness in sub-sea pipelines. Acoustic chemometrics was applied to investigate the potential for online estimation of wax deposition thickness in sub-sea pipelines. This feasibility study was carried out as a so called *piggy back* on experiments performed at Statoil research centre in Porsgrunn, Norway with real crude oil or waxy gas condensate. The first investigations focussed on the repeatability of the acoustic chemometric technique followed by online prediction of the wax deposition thickness in a single-phase oil flow pipeline. A partial least squares regression model was calibrated and validated with a totally independent data set. The calibrated model had a root mean squared error of prediction of 0.28 mm with a final wax deposition thickness of 3.36 mm, a slope of 0.91 and R^2 of 0.83 which were satisfactory results. The effect of varying oil flow rates on the wax deposition thickness was also investigated. The preliminary results showed the need for further investigations based on a robust experimental design and sample

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pre-processing. The general conclusion that can be drawn from this feasibility study was that the potential of adapting the acoustic chemometric technique for online estimation of the wax deposition thickness exist and must be further investigated.

Keywords: Acoustic chemometrics, partial least square regression (PLS-R), principal component analysis (PCA), wax deposition, single-phase flow

1 Introduction

There is an increase in demand for petroleum and its allied products due to the rapid increase in the worlds' population even though the worlds' oil production has reached its peak [1]. Several oil producing companies are now developing marginal oil wells and drilling in deeper depths below sea level as a result of the increase in demand coupled with the increase in price of crude oil on the international market. A major concern in the transportation of crude oil from oil reservoirs is flow assurance. Wax deposition in oil pipelines is a flow assurance issue. The deposition in sub-sea oil producing pipelines is one of the major obstacles for operating long sub-sea single-phase or multiphase flow pipes. Transportation of crude oil from the oil reservoir may result in the deposition of wax from the petroleum fluids. Wax precipitation is a result of cooling of the sub-sea pipeline by the ocean which is typically at a temperature of 4^{o}C whilst the reservoir temperature and pressure is between 70 – 150^{o}C and > 2000 psi respectively [2]. The heat transfer from the crude oil to the ocean is mainly a result of convection and conduction heat transfer. The temperature at which the first wax appears is commonly referred to as wax appearance temperature (WAT).

When wax deposits in oil pipelines, these deposits must be monitored continuously and removed when the deposits have the tendency to affect production. There are several methodologies that can be applied in removing the wax deposits including heating, pigging operations, addition of wax inhibitors whilst pipe line insulations can be applied in preventing wax deposition. All these methodologies have their advantages and disadvantages. Pigging is the most widely used operation in removing wax deposits in pipelines due to the advantages that this technique possesses over the others. Faster wax deposition in pipelines results in a more frequent and risky pigging operation [3]. When the wax is allowed to grow for a long period, the effective cross-sectional area of the pipeline is reduced. At higher wax deposition rates the tendency for the pigs to get stuck in the pipe is great. Aging of wax in the production pipeline is also an important area of research with respect to wax deposition. Several researchers have developed wax aging models and these models have been reviewed by Aiyejina *et al* [4]. In cases where production must be stopped in order to remove the plugged portions of the pipeline due to large wax deposits, the cost involved in replacement and downtime was estimated by Huang *et al* as ~$30,000,000 whilst in severe cases the platform could be abandoned at a cost of $100,000,000. Thus wax deposition can cause devastating economic implications to the oil producing company [2].

Wax deposition in pipelines is influenced by several factors including crude oil composition, temperature, flow rate, pressure and thermal history [5]. This flow assurance problem has been a major research topic for some time now. Several researchers have studied and proposed methodologies [6-11] for detecting wax deposition. Aiyejina *et al* [4] have reviewed wax formation in oil pipelines. In their critical review, deposition mechanisms including wax deposition models were captured. Hoffmann *et al* [12] proposed an online wax thickness build-up monitoring technique in sub-sea oil pipeline based on heat pulse monitoring. The

availability of a reliable and accurate online wax deposition thickness instrument/technique will be a major break through to the oil producing companies. This instrument if available will not only reduce the cost of production but also enable the oil producing companies to develop oil wells which contain high wax content. As a result of this development, the worlds' oil production would be increased to meet the demand of the ever growing population.

Acoustic chemometrics is a general process monitoring technique which has been adapted in several industries as an alternative process monitoring solution. Literature on the adaptation of the developed acoustic chemometric principle as an alternative process monitoring solution in the oil industry is limited since its inception. Arvoh *et al* [13,14], adapted the acoustic chemometric technique for online estimation of both the reject gas and liquid flow rates in a compact flotation unit for produced water treatment. From that study, it was clear that the potential application of this technique in the oil industry is bright. Acoustic chemometrics was the process monitoring solution considered in this feasibility study for online estimation of the wax deposition thickness in a single-phase sub-sea oil flow pipeline.

The feasibility study is a *piggy back* on the single-phase experimental investigations conducted and reported by Hoffmann and Amundsen [15]. The main objective for the experiments conducted in Hoffmann and Amundsen was to obtain experimental data to validate the basic assumptions of a model since field data from production pipelines are difficult to obtain. The experiments were conducted in a 50.8 mm (2 in) flow loop experimental facility at Statoil Research Centre in Porsgrunn, Norway. In these investigations real waxy gas condensate from the North Sea flows through a test section surrounded by water annulus to simulate sub-sea conditions. In this feasibility study both principal

component analyses (PCA) and partial least square regression (PLS-R) were applied to signals from the acoustic sensor to investigate the potential application of this technique for online estimation of the wax deposition thickness in a single-phase sub-sea oil pipeline. The reference measurements adopted in this study were based on pressure drop measurements and measured final wax deposition thickness by weight which was reported in [15]. The calibrated PLS-R model was validated with a fully independent data set. Evaluation of the model was based on the root mean squared error of prediction (RMSEP), slope, offset, correlation coefficient, explained residual validation variance plot and the score plots. The results for online estimation of the wax deposition thickness in this experimental study is presented and discussed. The results showed that the potential for adapting the acoustic chemometric technique for online estimation of wax deposition thickness in sub-sea pipelines exist and hence further research into the adaptation of this technique is currently ongoing.

2 Materials and method

Acoustic chemometrics was the technique of choice adopted for online estimation of wax deposition thickness in single-phase pipeline. The *piggy back* nature of these investigations was an advantage for proposing this technique since the measurements and data logging mechanism requires little/no supervision. Besides that, acoustic chemometrics also possesses several advantages over traditional monitoring principles which include:

- Online operation
- Real time predictions
- Easy clamp on sensors
- Non intrusive/invasive measurements
- Time saving with the use of empirical modelling

Whilst this technique possesses several advantages, the main disadvantage associated with this technique as with all other chemometric methods is the need for reference measurements. Besides that, this technique is considered a "point measurement" since in wax deposition the changes in wax deposition thickness in the pipeline occurs over several kilometres in the pipeline.

2.1 Flow loop

The wax deposition experimental test facility at Statoil research centre in Porsgrunn, Norway consist of a flow loop where real crude oil or gas condensate is circulated from a tank to the test section (Fig. 1). For detailed description of the experimental facility interested readers are referred to Hoffmann and Amundsen [15]. In this feasibility study only a brief description of the experimental facility is presented. The 5.5 m long test section is surrounded by an annulus through which the counter current water flows. Both the oil and water temperatures in the experimental facility can be adjusted separately between 5^{o}C and 70^{o}C, implying that different temperature conditions can be investigated. The total volume of crude oil or gas condensate in the tank was 2000 L, thus wax depletion during the experimental period was not an issue. The experimental rig was operated with crude oil and gas condensate at atmospheric pressure. The rig was equipped with a pump capable of delivering crude oil or gas condensate with volumetric flow rates in the range of 3 – 30 m^3/h. A coriolis flow meter was used to monitor the volumetric flow rate (Table 1). Stainless steel pipe with 50.8 mm (2 in.) internal diameter was used in these experiments.

2.2 Experimental

Waxy condensate from a North Sea receiving terminal was used in all single-phase experiments investigated in this study. The main process parameters for this waxy condensate are presented in Table 2. The first experimental investigation focused on the repeatability of the experiments. In each experimental investigation, the rig was circulated with fluid at a temperature of 60^{o}C to melt any wax deposited in the pipeline during the previous experiments for a period of 6 h. After this stage, both the oil and water temperatures were set to the desired point. Flow rate and pressure drop measurements were used to verify the removal of all deposited wax in the pipeline. Then the temperature of the water through the annulus was reduced to the target and maintained over the experimental period. The temperature variations within each experimental period were kept at 0.2^{o}C whilst that of the flow rate was maintained at 0.1 m^{3}/h. On completion of each experiment which was normally two days for experiments to investigate the repeatability, the pipe was drained and the test section removed to measure the thickness of the deposited wax. Including the repeatability/replication experiments, the total experimental period was normally within 5 days for each experimental run.

2.3 Acoustic chemometrics

Adaptation of the acoustic chemometric technique in the area of science and technology has matured since it was first developed. A general description of the theory and principles of acoustic chemometrics can be found in [16] and hence only a brief description of this technique is explained here. Four miniature accelerometers from Brüel and Kjær® model 4519 with high resolution giving an excellent signal to noise ratio was used to acquire the acoustic signals. The accelerometers can operate within -51^{o}C and 100^{o}C whilst the mounted resonance frequency of the accelerometers was 60 kHz. The accelerometer was glued onto the

pipe and since the annulus would be field with water, the connection between the accelerometer and the connecting cable was covered with epoxy (Fig. 2, left), to prevent the damage of the accelerometer by water. The connecting cables were also protected from the flowing water caused by capillary action. The time domain signals from the accelerometer were first amplified to the maximum possible digital resolution of the analog-to-digital converter in a Signal Amplifying Module (SAM). Unwanted frequencies were attenuated with a band pass filter. After which a fixed number of samples (4096) were transformed with Blackman Harris window transformation [17] function to reduce spectral leakage. Fast Fourier Transformation (FFT) was used to transform the time domain signals into frequency domain. This transformation aids in the comparison of acoustic spectra acquired at different time periods. The sampling frequency selected in these experiments was 300 kHz. Each acoustic spectrum was a result of an average of 200 acoustic spectra.

There were two heating coils on each of the separate pipes in the test section and on each of the separate pipes, two accelerometers were glued. The heating coils were used by Hoffmann and Amundsen in their investigations on wax deposition by the principle of heat pulse. The signals from the accelerometers were hugely affected by the heating coil due to the creation of turbulence in the flow caused by the heating coils close to the accelerometers and electromagnetic noise. Three of the connections between the cables and the accelerometers were not tight enough thus after a while, the counter current water flowing through the annulus found its way into the accelerometers and subsequently damaged them. From this occurrence, only one of the accelerometers in the test section was used in these acoustic chemometric investigations. The heating coil on the pipe where this remaining accelerometer was glued was removed to reduce the effect of measurement noise. With one accelerometer, the feasibility study was carried out and with these promising results, further investigations

could be carried out including monitoring the wax deposition at different positions on the pipeline. All results and discussions in this document were based on only one accelerometer.

2.4 Reference measurements

Pressure drop measurements across the test section in combination with the final weight of the deposited wax were considered as the reference. Below the WAT, wax starts to deposit on the inner wall of the test section, thus the effective cross sectional area and the wall roughness changes which results in changes in pressure drop. Hoffmann and Amundsen described three main methods in determining the wax deposition build-up. In this feasibility study, two of the methods were combined in view of obtaining a more accurate wax deposition profile. By measuring the increase in pressure drop, the wax deposition build-up can be determined [15] from Haaland's friction factor correlation [18]. The inner diameter of the test section can be solved numerically from;

$$F(D) = \frac{D^5 \pi^2 \Delta p}{8 \rho_{oil} Q^2 L} - \left(1.8 \log_{10} \left(\frac{6.9 D \pi \eta_{oil}}{4 Q \rho_{oil}} + \left(\frac{\varepsilon}{3.7 D} \right)^{1.11} \right) \right)^{-2} = 0 \qquad (1)$$

Where D is the inner pipe diameter, Δp is the pressure drop, Q the volumetric flow rate, ρ density of oil, L length of the differential pressure measurement, η is the viscosity of oil and ε is the surface roughness of the inner pipe wall.

The wax thickness build-up data from pressure drop measurements was a bit noisy. With measurement noise in the reference data, the prediction properties of the model can be adversely affected. In order to smooth the noisy measurements from the reference, a non-linear function was used in fitting the data points. The data from the wax build-up from the pressure drop measurements were then fitted with a non-linear function. Fig. 3 shows an

illustration of the wax thickness build-up from pressure drop measurements and its corresponding non-linear function. From this figure, it was observed that the non-linear function was bias at the beginning of the curve and hence the pressure drop measurements were used as the reference measurements and the impact of the noise assessed.

The final weight of the test section can provide accurate information on the final thickness of the deposited wax in the pipeline when measured on completion of the experiment. The thickness of the wax layer was calculated from the measured density and the calculated cross sectional area of the pipe. In this calculation, it was assumed that the deposited wax was evenly distributed throughout the entire cross section of the pipe which in real application in single-phase wax deposition in sub-sea pipelines can be considered to be an accurate assumption. A removable part of the test section was used to visually inspect the wax deposit and to measure the weight of the deposited wax. From the final weight measurements, the wax deposition thickness was calculated. The predicted wax deposition thicknesses from the pressure drop measurements were not as accurate as the calculated wax deposition thickness. Hence, the calculated wax deposition thickness was used to improve the accuracy of the pressure drop measurements. Thus a combination of the pressure drop measurements and the calculated wax deposition thickness were used as the reference measurements in these experimental investigations.

2.5 Multivariate calibration

Principal component analysis (PCA) and partial least squares regression (PLS-R) were the multivariate data analysis techniques employed in this study. Both PCA and PLS-R are the most commonly used data analysis techniques in the chemometric community.

2.5.1 Principal component analysis

PCA constitute the basis of multivariate data analysis. PCA is essentially a data compression technique, were the data matrix (sensor measurements), **X**, is decomposed into an "information" part and a "noise" part. The **X** data matrix must contain the information of interest which is a requirement in all data analysis techniques. In traditional models, the number of samples (N) is usually lager than the number of variables (K) where K may be measurements from sensors (e.g. temperature, flow, pressure, pH, etc). However in modern applications of PCA, it is common to include spectral data (γ-ray, X-ray, acoustic signal, NIR, IR, UV etc) and chromatographic data (HPLC, GC, TLC, etc) [19]. Thus in modern use, K is often larger than N. Signal pre-processing is vital in improving the information in the sensor measurements. Common pre-processing techniques include:

- Subtracting the mean from each column
- Scale each column e.g. by dividing by the standard deviation

PCA and PLS-R are mostly applied in cases where there is collinearity between the variables in the **X** data matrix [20]. The term collinearity means that in the matrix **X**, there exists some dominating type of variability that carries most of the available information. The main information in the variables $\mathbf{X} = \{\mathbf{x}_k, k = 1,2,...K\}$ is compressed into $\mathbf{T} = \{\mathbf{t}_1,...\mathbf{t}_A\}$ $(\mathrm{A} < \mathrm{K})$, which is called the principal components scores of **X**. The intensity of variability explained by each factor is shown by the magnitude of the eigenvalues. The columns of the score vectors, T, are orthogonal to each other and in addition, the columns of the loading vectors, **P**, are also orthogonal to each other. Thus, the **X** data matrix can be split into

$$\mathbf{X} = \mathbf{T}\mathbf{P}^{\mathrm{T}} + \mathbf{E} \tag{2}$$

Where $\mathbf{T}\mathbf{P}^{\mathrm{T}}$ constitute the information part and **E** is the **X**-residuals matrix (measurement noise). When A=K all the eigenvectors (**T**) can be extracted, implying that $\mathbf{X} = \mathbf{T}\mathbf{P}^{\mathrm{T}}$. The most commonly used algorithm is the NIPALS algorithm and can be found in [20, p.111] and

a detailed description of the theory, application and practical examples can be found in [19-21].

2.5.2 Partial least squares regression

Partial least square regression was used to calibrate a model for online prediction of the wax deposition thickness in a single-phase pipeline. The theory, principles and application of PLS-R can be found in literature [20,22], and thus only a brief description of this technique will be presented. Partial least square regression (PLS-R) is a statistical data modelling technique which aims at finding an empirical model that relates a matrix (**X)** and reference vector (**y**). During PLS-R modelling, the linear relationship between **X** and **y** data sets are extracted. The significance of PLS-R has gradually grown in many fields including physical and analytical chemistry, pharmaceutical and industrial process monitoring and control [22]. In PLS-R, the **y** variable is used to guide the decomposition of the **X** data matrix and thus balances the information in both **X** and **y** resulting in reduction of irrelevant PLS components in the calibrated model [20]. The NIPALS algorithm is the most widely used algorithm in PLS regression and multivariate data analysis software. In this algorithm, the intention is to describe both **X** and **y** simultaneously and make the error as small as possible and at the same time extract as much useful information from the **X** matrix in order to describe the **y** response variable [22]. In evaluating the regression model the root mean squared error of prediction (RMSEP), offset, slope and correlation coefficient are commonly used. Besides these, visual evaluation of the relevant score plots, loading weights plots, explained variance plots also provide useful information for calibrating and development of the prediction model. The root mean squared error of prediction (RMSEP) is calculated as:

$$\mathrm{RMSEP} = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{y}_{i,\mathrm{predicted}} - y_{i,\mathrm{reference}}\right)^2}{n}} \qquad (3)$$

2.5.3 Sample pre-processing

In both PCA and PLS-R, sample pre-processing can result in the extraction useful information from the sensor measurements. That is, spectral pre-processing has the tendency to improve the models predictive properties when correctly applied. There are several pre-processing techniques that can be applied to the spectral data acquired by the accelerometers. The most commonly used pre-processing technique in acoustic chemometrics is mean centring and variance scaling. The time duration for each wax deposition experiments presented in this feasibility study was 2 days in the repeatability experiments and 5 or more days in the experiments for developing models for online wax deposition. A 5 min. sampling frequency was selected during the data acquisition process. This means that for each experiment 1440 acoustic spectra (corresponding to 5 days) were acquired and logged by the data acquisition devices. Wax deposition in sub-sea pipeline occurs over a period of time and the growth also depends on the process condition and the amount of wax in the oil. The 5 min. sampling frequency in these investigations were considered good enough to capture the relevant information in relation to the wax growth in the pipeline. However, the sampling frequency can be increased or decreased in future investigations if there is the need. Each acoustic spectrum consists of frequencies up to 150 kHz. Fig. 4 (top) shows a raw acoustic spectrum before sampling pre-processing.

A moving average from a rectangular 366 Hz window size was computed for all samples in the variable direction. Fig. 4 (bottom) shows the same spectrum as the one on top after pre-processing. From this figure, a clear symmetry can be observed from frequencies between 44 kHz and 150 kHz of which the line of symmetry can be drawn at 94 kHz. In PCA and PLS-R calibration, mean centring and variance scaling was applied to the **X**- data matrix.

3 Results and discussion

The results from this feasibility study based on principal component analysis and partial least squares regression were presented and discussed. This feasibility study being the first of its kind in the application of acoustic chemometrics for online wax deposition estimation in single-phase sub-sea pipelines, the first data analysis technique investigated was PCA followed by PLS-R.

3.1 The first acoustic chemometric test

PCA was applied to the data sets obtained from the accelerometer to investigate the potential application of this technique for estimating wax deposition. If the results from this study did not possess an indication of growth in wax thickness, then this research would have been terminated. Two of the data sets from the experiments conducted during these first tests are presented and discussed to show that there was a potential for further investigations. Fig. 5 shows score 1 (t_1) from the principal component analysis plotted as a line for two independent data sets. The differences between these two experimental data were in their fluid properties and process conditions. The oil inlet temperature and the oil flow rate (Fig. 5 Right) were set at 24^{o}C and 5 m^3/h respectively while those in Fig. 5 left were set at 19.4^{o}C and 5 m^3/h respectively. From the principal component (PC) score 1 (t_1), an increase in time duration resulted in an increase in the magnitude of the score values (Fig. 5).

The increase in magnitude of the score vector can be associated with the wax deposition in the pipeline. The shape of the score vector in Fig. 5 can be considered to be similar. The difference in the shape of the score vector can be associated with the difference in set point temperature and the density of oil used in the experiments. Research have showed that the oil temperature has a major impact on wax deposition in oil pipelines [5,23] thus for

measurements from the acoustic sensor to show differences in the growth of the deposited wax was a promising indication of the potential of the technique. Even though the sampling frequency for both data sets was the same, more samples were used for calibration in the score plot on the left than the right. This difference in the number of samples can be associated with the frequency with which the heater was turned "on" and "off". Its important to state hear that the first presented results were based on calibration with measurements from the acoustic sensors without any additional information relating to wax deposition, process conditions and process fluids.

3.2 Interference caused by temperature control

As describe earlier (Materials and method section), the heater in the other section was used to investigate wax deposition thickness based on heat pulse [12]. The frequency with which this heater was switched on was set and after which the heater was operated automatically. After the first experimental investigations, PCA was again performed on the data set to determine whether or not this heat pulse measurement principle had any significant impact on the acoustic spectra. The score plot from the PCA for one of the data sets is presented for analysis and discussion (Fig. 6). The experimental result presented here was conducted over 5 days. After the 5 experimental day's period, the process data was extracted and analysed. From the process data, it was concluded that the heater was on for about 25% within the 5 days. There was considerable number of samples on the left of the score plot as compared to the right (Fig. 6). This goes to show that the heater was turned "off" most of the time in this particular experiment. Bearing in mind that the time interval for acquiring each acoustic spectrum was 5 mins and on extracting the data from the "off" measurements it was calculated that 75% of the total data was recorded when the heater was "off" which was consistent with data from the process conditions. In regression modelling, having two distinct groups for a single

experiment would have a negative impact on the models predictive ability and thus is generally not recommended. Thus either the "on" or the "off" measurements could be considered for model calibration. Since the "off" measurements had higher number of samples than when the heater was "on", the measurements acquired when the heater was switched "off" were recommended and were subsequently extracted and used for calibrating and predicting the wax deposition in the pipeline from this point onwards. In real sub-sea oil production applications, there are no heaters and thus all the signals from the acoustic sensors would be grouped in the same proximity in the principal component space. Hence there would be no need to extract portions of the data based on principal component analysis before model calibration and validation.

3.3 Online wax thickness estimation

Hoffmann and Amundsen [15] in their earlier investigations conducted experiments to verify the reproducibility of wax deposition in this experimental rig. From their investigations, they concluded that the wax deposition in the single-phase investigations were reproducible. With this at the background, experiments were conducted to investigate the wax deposition thickness in a sub-sea pipeline based on acoustic chemometrics. Two of the independent experimental data sets are presented and discussed to determine whether or not acoustic measurements coupled with partial least squares regression can be adapted as a useful alternative to estimate the wax deposition thickness in the pipeline. A model was calibrated and further validated with an independent data set for prediction the wax deposition thickness. Each of the experiments in both the calibration and validation data sets was conducted within a period of 5 days, with similar process and operating conditions. The oil flow rate was set to 10 m^3/h whilst that of the coolant was set at 5 m^3/h. The calculated wax thickness from the weight measurements was 3.26 mm for the calibration experimental data whilst the validation

experiment was 2.98 mm. Fig. 7 (left) shows the residual validation variance plot for the model. From the residual validation variance plot, 2 PLS components were considered to be optimum for model calibration. With 2 PLS components, 82% of the information related to the wax deposition thickness in the pipeline was extracted by the model. The time series plot showed the trend of growth in the thickness of wax in the pipeline during the experimental period which was used as an aid in assessing the models predictive properties. The predicted test set validated wax deposition thickness by the model (Fig. 7, Right) conveyed a real picture of the models' predictive power/properties in future predictions. From this model, the root mean squared error of prediction (RMSEP), slope and R^2 were 0.28 mm, 0.91 and 0.83. A correlation coefficient of 0.97 indicates the existence of a strong linear relationship between the predicted wax deposition thickness and the reference measurements. The nature of the curve for the predictions can also be considered to be similar to that of reference pressure drop measurements. The accuracy with which the model predicts the wax deposition thickness at this stage of the research was satisfactory and promising bearing in mind that this model was validated with fully independent data set. Even though these promising results were achieved at this stage of the research work several factors affecting wax growth need to be considered including other pre-processing techniques.

The loading weights plot gives information on frequencies that were considered important to the calibrated model. The loading weights plot (Fig. 8) shows that frequencies up to 70 kHz were more important for calibration and prediction. This was not a surprise since the resonance frequency of the accelerometer was 60 kHz. Calibrating a model with frequencies slightly above the resonance frequency of the accelerometer (up to 70 kHz) did not improve the models predictive properties. Thus all frequencies acquired by the acoustic sensor were used for model calibration and recommended in future applications.

3.4 Varying oil flow rate

The effect of varying flow rates on wax deposition have been studied by several researchers, whilst in the acoustic chemometric community several researchers have studied the impact of varying flow rate on the acoustic signals. The general conclusion that has been drawn in the application of acoustic chemometric in relation to varying flow rates was that, increasing flow rate resulted in a corresponding increase in peak amplitudes in the acoustic signals. The question that comes to mind here is, "does the increase in peak amplitudes of the acoustic signals corresponds to an increase or decrease in the wax deposition thickness?" Both Creek *et al* [10] and Hoffmann and Amundsen [15] studied single phase wax deposition, they concluded that increasing flow rate under the same process conditions resulted in a decrease in the wax deposition thickness in the pipeline. The relationship between flow rate and wax deposition thickness was found to be in the form of a non-linear function in both investigations. Most of the models presented in literature with respect to investigating the effect of flow rate on the acoustic signals were based on finding a linear relationship between the increase in flow rates and the magnitude of the acoustic signals. This thus necessitates the need to investigate the effect of flow rate on the acoustic signals in relation to estimating the wax deposition thickness in a single-phase sub-sea oil pipeline.

In these investigations, three sets of oil inlet flow rates (11.8 m^3/h, 12.8 m^3/h and 13.8 m^3/h) were considered, whilst the process conditions were kept constant within the experimental period. The inlet oil temperature was set at 27^oC whereas the inlet water (coolant) flow rate was12.5 m^3/h. The experiments with flow rate 11.8 m^3/h and 12.8 m^3/h lasted for 4.8 days whilst the last experiment was conducted over a period of 10.9 days. The wax thickness profile generated by the pressure drop measurements for experiments with 11.8 m^3/h, 12.8 m^3/h and 13.8 m^3/h volumetric flow rates can be approximated as h(wax)~t^0.56,

h(wax)~t^0.69 and h(wax)~t^1.03 respectively. Where h is the wax deposition thickness and t is time in minutes. The wax deposition thickness calculated based on the weight of the deposited wax for 11.8 m^3/h, 12.8 m^3/h and 13.8 m^3/h flow rates were 0.55 mm, 0.52 mm and 0.89 mm respectively. Several models were calibrated with data from one of the flow rate measurements and validated against the others. The results from these models were not acceptable. Again, models were calibrated with two of the data sets and validated against the data not included in the calibration. The results again from these multivariate data analysis were not acceptable. Even though the methodology performed well internally within the calibration data set, the results from validating the model were not acceptable. The general observation was that the acoustic spectra for the different flow rates lay in different principal component directions whilst those of the same flow rate lay in the same direction (Fig. 9).

From Fig. 9, the scores for the different flow rate did not increase from the left to the right. This score plot can be used to explain the difficulty in calibrating a model from one or two of the data sets and validating with the remaining. This occurrence was seen and reported by Arvoh *et al* [24] where gamma measurements combined with multivariate data analysis was applied to estimate volume fractions and to identify flow regimes in multiphase flow. In that publication, they were able to develop a technique to compensate for the difficulty in accurately predicting the component volume fractions since there were considerable experimental data available. This finding has not been encountered in previous studies where acoustic chemometrics has been applied. To further investigate these results, an experimental design with varying flow rates should be drawn and experiments conducted in developing models capable of accurately predicting the wax deposition thickness in the pipeline with varying oil flow rate.

4 Conclusion

Wax deposition in oil producing pipelines can have devastating economic implications to the oil producing companies. Several researchers have studied the mechanism involved in wax deposition, but as of today *off the shelf* instruments for online prediction of wax deposition thickness in oil producing pipelines are not available. Acoustic chemometrics was been adapted for online estimation of wax deposition thickness in a single-phase oil flow pipeline based on *piggy back* investigations. The first tests were conducted to investigate the potential of applying this acoustic chemometric technique. The resulting experimental data were analysed by principal component analysis. A line plot of score 1 showed a relation which was attributed to the wax thickness growth in the pipeline. These first results showed that the potential for the adaptation of the acoustic chemometric technique exist. Partial least squares regression technique was applied to calibrate a model from one data set and validated against an independent test data. The results from this PLS-R modelling showed that the wax growth could be predicted with satisfactory accuracy. The effect of varying flow rates on wax deposition thickness based on acoustic chemometrics was also investigated. The preliminary investigations showed that the samples from the same flow rate lay in the same principal component space and samples with varying flow rate also lay in different component space. The experiments with varying flow rates needs to be repeated and other pre-processing techniques also investigated to develop a model capable of predicting the wax deposition thickness under varying flow rates.

5 Future work

The feasibility study showed that the potential application of the acoustic chemometrics technique for online estimation of the wax deposition thickness in a single-phase oil

producing pipeline is bright. The results from this feasibility study would form the basis for future developments of this technique. Areas of further investigations include:

1. Design a robust experimental procedure to investigate the effect of varying oil flow rate on the wax deposition thickness based on acoustic measurements.
2. Effect of varying various process parameters including temperature, pipe diameters and waxy crude
3. Develop a model for online prediction of wax deposition thickness in both single-phase and two-phase fluid pipe flow.
4. Scaling ups
5. Develop a global model for online estimation of wax deposition thickness and test for its robustness.

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Fig. 8. Loadings weight plot showing the 1st and 2nd PLS components. This plots shows that all frequencies can be considered to be important for model calibration even though frequencies less than 70 kHz (left half) were considered to be more important.

Fig. 9. Score plot for the 1st and 2nd principal components for experiments with varying oil flow rate in m^3/h. The score plots shows three clear groups for the respective flow rates.

Tables

Table 1. Instrumentation [15]

Table 2. Fluid properties

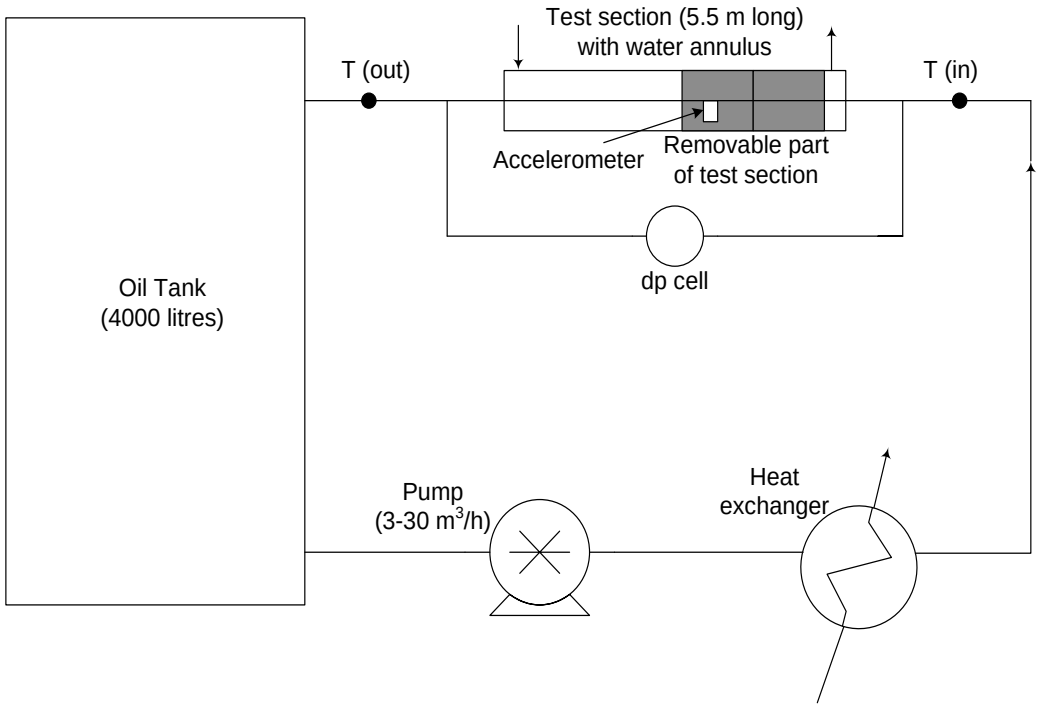


Fig. 1. Experimental wax deposition test rig [16]

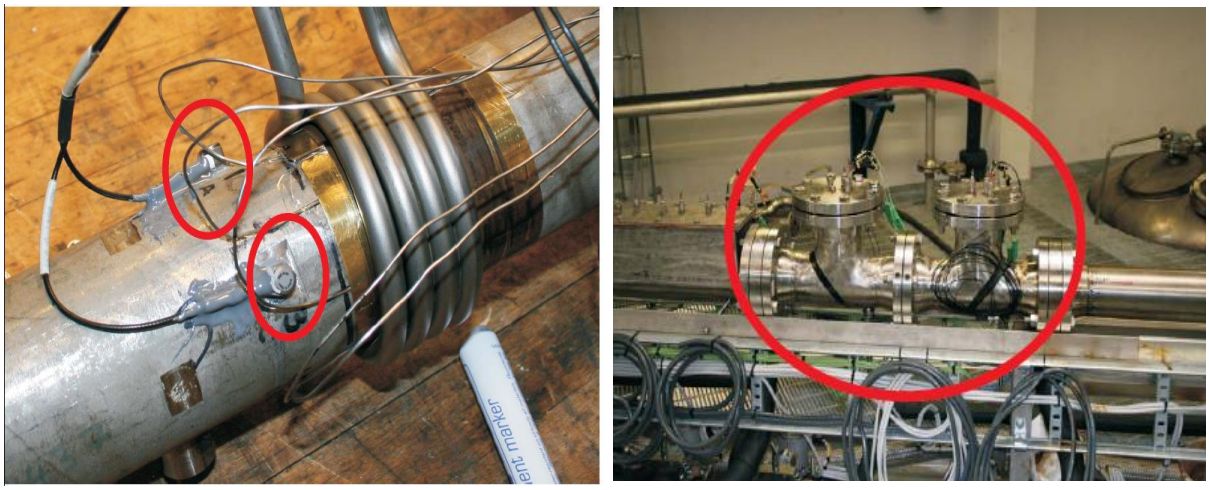


Fig. 2. Left: Accelerometers connection on the 2 in. test section. Right: The test sections comprise of two 2 in. pipes. The installation on the left was not suitable in this application. The accelerometers were glued onto the pipeline.

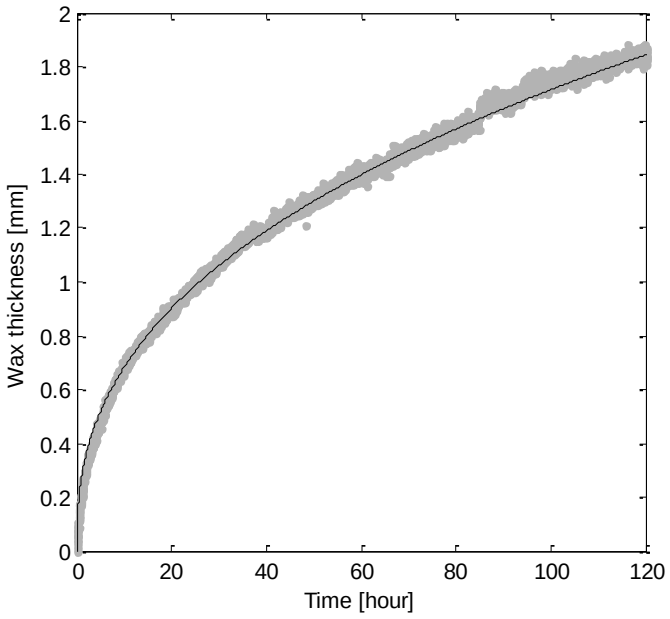


Fig. 3. Wax thickness build-up from pressure drop measurements data and a non-linear fitted function. The non-linear function was bias at the beginning of the measurements; hence the pressure drop measurements were used in subsequent investigations

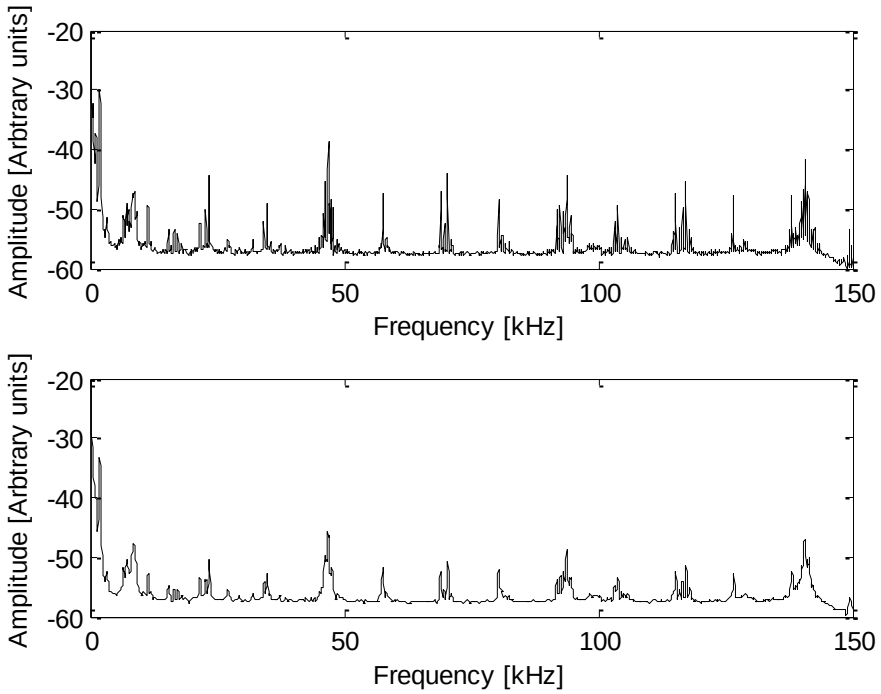


Fig. 4. Acoustic spectrum before pre-processing (top) and after pre-processing (bottom). A moving average of 366 Hz frequency was computed to smooth each acoustic spectrum

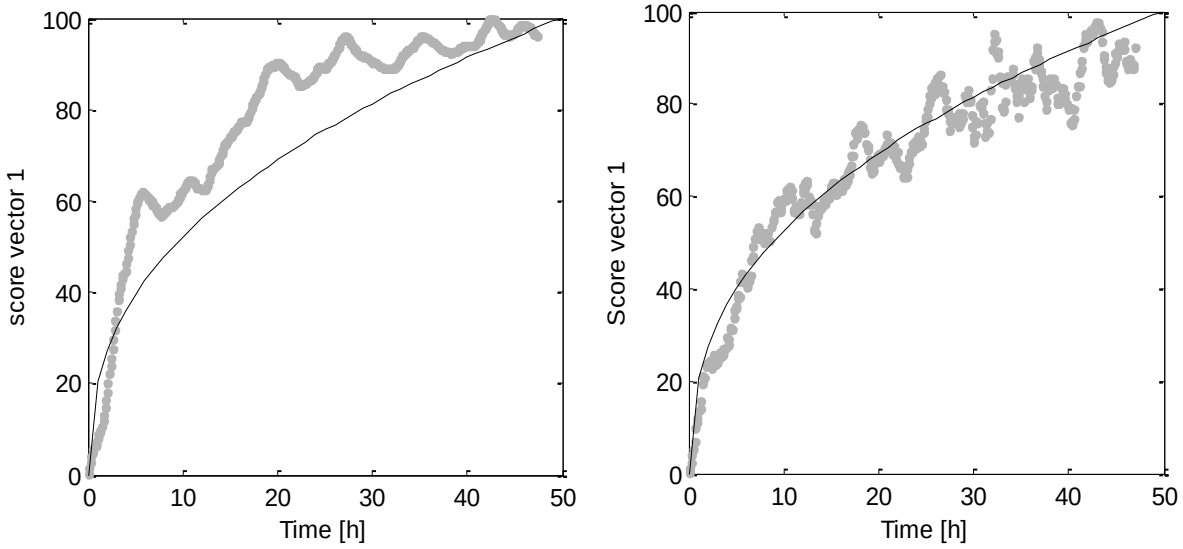


Fig. 5. Principal component analysis score 1 for two independent data sets. The two figures show the growth of the wax deposits in the pipeline for their respective experiments. The nature of the curves show that the wax deposition thickness increases with time. The difference between the wax growths in these two figures can be associated with the temperature difference and the oil density

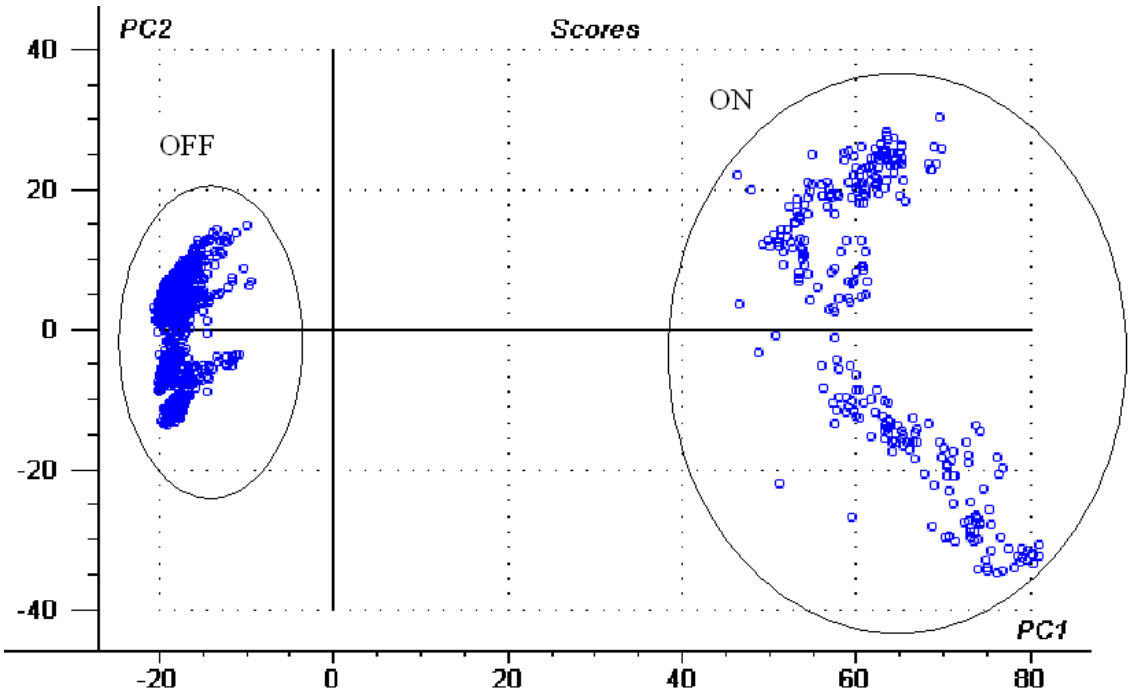
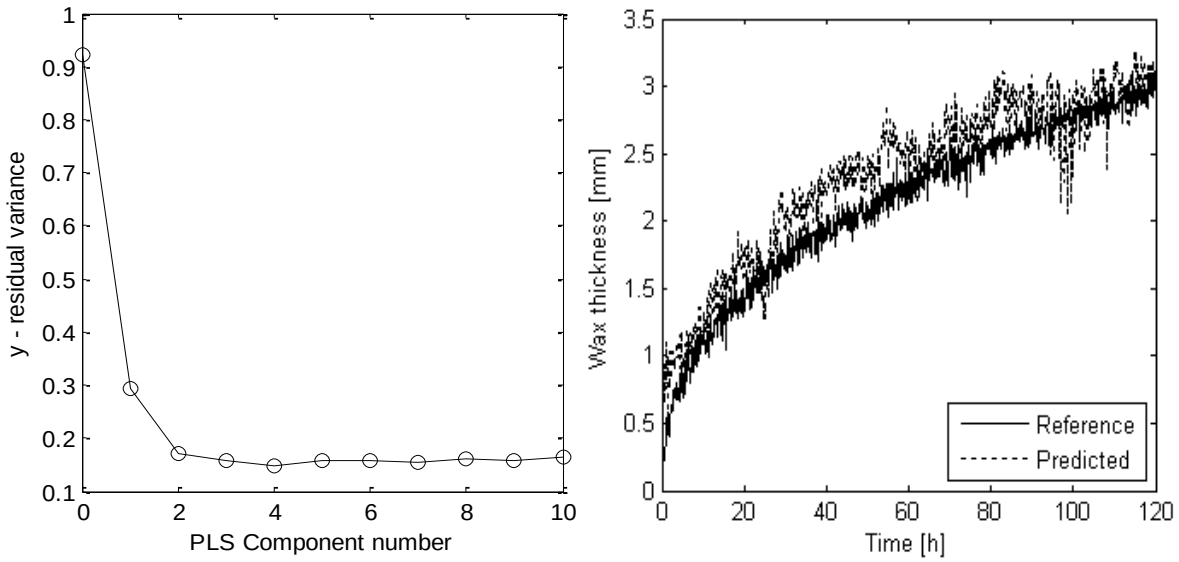


Fig. 6. Principal component analysis scores 1 & 2 to illustrate the heater being either on or off. From this figure, two clear groups can be seen and more data was acquired when the heater was off



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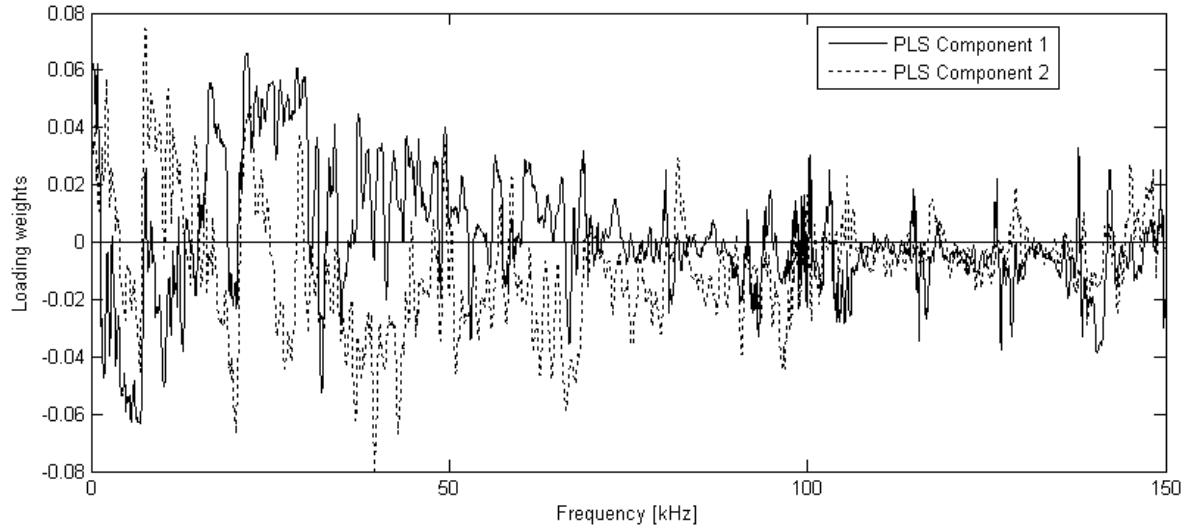

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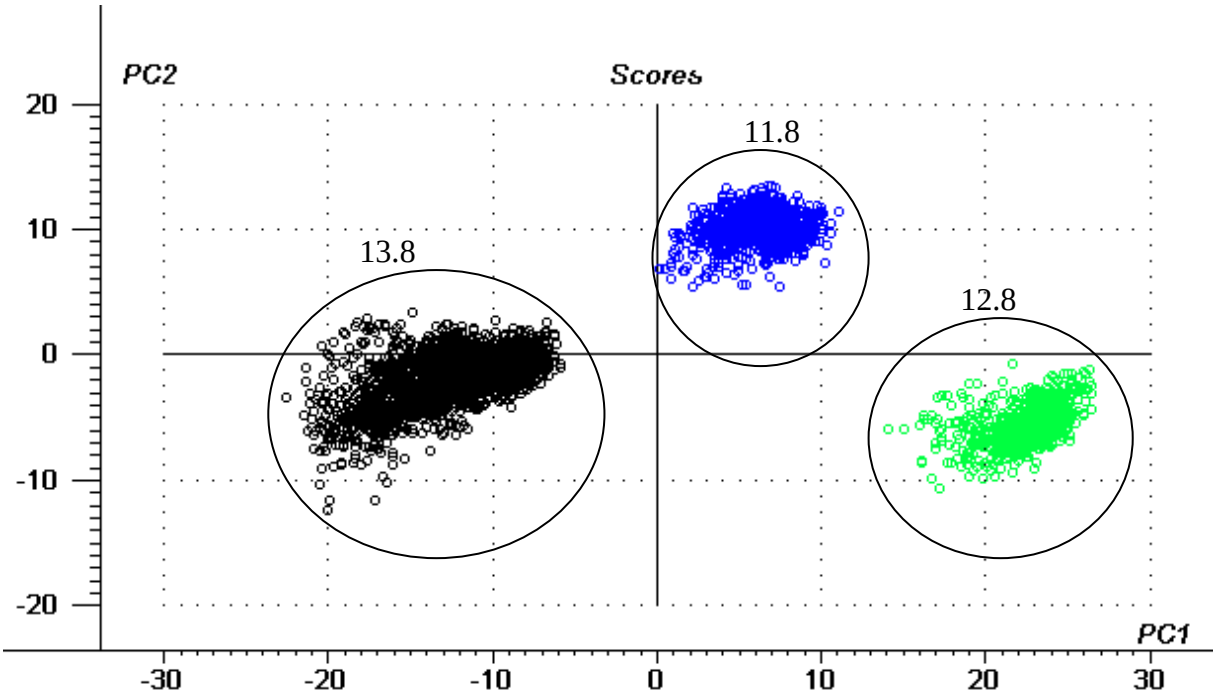

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Table 1. Instrumentation [15]

	Mass flow	Differential pressure	Temperature
Instrument	E&H Coriolis Promass 63 F	Rosemount 3051 cd2	Rosemount k-element
Accuracy	± 0.1% of reading	± 0.065% of calibrated range	± 0.5°C
Range	0-31 m^3/h	0-620 mbar	-100 – 1300 °C

Table 2. Fluid properties

Density of oil	809 kg/m^3 measured at 20^{o}C
Wax appearance temperature (WAT)	≈ 30 ^{o}C
Pour point	1 ^{o}C
Wax content in oil	≈ 4.5%