Estimation of gas/liquid and oil/water interface levels in an oil/water/gas separator based on pressure measurements and regression modelling

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Abstract

Gravity separators are widely used for separation of gas/oil/water/sand from both offshore and onshore oil production facilities. Estimation of the gas/liquid and oil/water interface levels in gravity separators have been a concern since these parameters are important for reliable operation. Most of the instruments on the market today do not provide reliable measurements of both gas/liquid and oil/water interface levels. The few instruments that do provide reliable measurements are however based on radioactive principles. Nevertheless these radioactive instruments possess a strong health, safety and environmental risk. An alternative inexpensive, environmentally friendly, accurate and cost effective way for gas/liquid and oil/water interface level estimation based on pressure measurement is presented. The root mean squared error of prediction (RMSEP) for gas/liquid and oil/water interface level estimation from traversing a pressure sensor based on partial least square regression (PLS-R) were 14.5 mm and 17.7 mm respectively. A comparison of results from models based on PLS-R and ordinary least square regression (OLS-R) techniques proved that the RMSEP from the PLS-R technique was better in estimating the oil/water interface level but in the case of gas/liquid interface level estimation the OLS-R technique was slightly better. It was concluded that the PLS-R technique provided a better overall result and is recommended

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when pressure measurements in combination with multivariate data analysis is applied for gas/liquid and oil/water interface level estimations in gravity separators.

Keywords: level estimation, gravity separators, partial least squares regression, pressure sensors, ordinary least squares regression

1 Introduction

The first stage in production of oil and gas from oil and gas wells is transportation of multiphase mixture (gas/oil/water/sand) through long production pipe lines to a high pressure separator (primary separator). The multiphase mixture is initially separated and transported for further processing. Efficient separation of gas, oil, water, and sand is of critical importance to achieve the desired production rate. Many of today's separation systems are based on gravity where the gas is vented off at the top, solids present in the mixture removed at the bottom, and the oil and water separated after settling. Separation is accomplished by the difference in densities between the oil and water. When the magnitude of the density difference between oil and water is large, the separation process is enhanced whilst a slow separation process is expected with a low density difference. The longer the residence time better separation is achieved, however a shorter residence time and a highly efficient separation is desired with respect to production rate. Research into optimizing the various stages in the refining of petroleum and its allied products has increased since the world's oil production has reached its peak [1]. Even though there has been considerable increment in the development of marginal oil wells due to the increase in price of crude oil on the international market, the demand of petroleum products far exceeds the supply. One way of increasing the supply of refined crude oil is to optimize the separation stage. The controllability of gravity separators significantly affects the efficiency of the separation process. Improving the process control of gravity separators will subsequently improve the accuracy of gas/liquid and oil/water interface level measurements [2]. The gas/liquid and oil/water interface levels were measured from the bottom of the separator.

There are basically two main types of gravity separators (horizontal and vertical) and the main parameters for selection of either of these separators are normally based on availability of free space and volumetric flow rates of both liquid and gas. In general the horizontal separators are popular in industry as compared to their vertical counterpart. When the volume fraction of the liquid components (oil and water) in the multiphase flow mixture is higher than the gas, horizontal separators are preferred due to the longer residence time and larger surface area whilst in cases where the multiphase mixture is predominantly gas, vertical gravity separators are preferred. There are several instruments on the market today that can accurately measure the gas/liquid interface level in gravity separators. However, the accuracy of the oil/water interface level measurements from most of these instruments is unacceptable. The few available instruments that can provide accurate gas/liquid and oil/water interface level measurements are based on radioactive measurement principles. These radioactive instruments possess strong health, safety and environmental risk and with very high instrument cost, thus their demand on the market has not grown as expected. Presently, operators of these separators sometimes need to visually inspect, read and record the gas/liquid and oil/water interface levels. This research work provides an alternative cost effective, environmentally friendly, accurate and simple to install gas/liquid and oil/water interface level estimation method based on pressure measurements and regression modelling.

Hjertaker *et al* [4] presented interface level monitoring developments which included electrical, ultrasonic, thermal and nucleonic principles. The obvious benefits and limitations were presented and also suggested the need for information relating to the qualitative comparison of these monitoring principles. Behin and Aghajari [5] conducted an experimental study in a pilot scale oil/water gravity separator by varying the water level at a constant total feed rate. They concluded that the optimum separator performance took place at a water level in the middle of the experimental range. A novel, non-invasive method for measuring the liquid level in a closed metal under high pressure based on ultrasonic lamb wave propagation along the tank walls has been reported by Sakharov *et al* [6]. They did not provide any information on the potential application of their novel technique in measuring the oil/water interface level. Woodard *et al* [7] presented a recently developed wireless measurement acquisition system for fluid-level measurement that has the potential of alleviating the shortcomings of fluid level measurement methods currently in use. The measurement principle was based on passive-inductor capacitance circuit which is not subject to mechanical failures. Fernandes *et al* [8] showed from the experimental results that image detection and treatment methodology was capable of measuring organic/water interface level in a mixed-settler based on phase inversion system. Lai *et al* [9] demonstrated the feasibility of a dual-pressure-sensor system comprising of a fibre Bragg grating based pressure sensor and a Fabry-Pérot cavity-based pressure sensor for obtaining simultaneous measurements of the level and specific gravity of liquids. Skeie *et al* [10] applied multi sensor data fusion for level estimation in a separator. Their first study showed that it was possible to use standard pressure sensors and data fusion to estimate the level in an oil/water separator. An overview of these and other technologies presently being applied in gas/liquid and oil/water interface level measurements are presented in [3,13-15].

The work described in this paper is a continuation of the work reported in [11] and [12]. In [11] and [12], the goal was to develop a soft sensor technique based on pressure measurements and multivariate calibration to estimate gas/liquid and oil/water interface levels in a vertical oil/water separator. This work focuses on testing the hypothesis that the accuracy of the gas/liquid and oil/water interface level measurements can be improved by increasing the number of pressure measurements. The data obtained from an experimental design was compared with a data set obtained by simulating the operation of the gravity separators to examine the impact of measurement noise on the experimental data sets. Finally, the accuracy in estimating the gas/liquid and oil/water interface levels based on partial least squares regression (PLS-R) and ordinary least square regression (OLS-R) modelling was assessed.

2 Materials and method

The study focused on calibrating, validating and subsequently predicting the gas/liquid and oil/water interface levels from measurements obtained by traversing a pressure sensor in a vertical gravity separator. PLS-R and OLS-R modelling techniques were adopted to investigate the accuracy in estimating the gas/liquid and oil/water interface levels. Finally, the effect of measurement noise was assessed with data obtained from a simulation of the operation of the gravity separator.

Increasing the number of pressure sensors mounted on the gravity separator can be accomplished by traversing a pressure sensor from the top to the bottom of the separator. This reduces the cost in purchasing several pressure sensors and also the intervals between pressure measurements can be reduced as much as possible thus increasing the accuracy of the measurements. A stepper motor was used to drive the pressure sensor in the separator this enhances the reproducibility of the gas/liquid and oil/water interface level measurements. The pressure profiles obtained from traversing the pressure sensor were the inputs to the PLS-R and OLS-R models.

2.1 Experimental facility

The potential of improving the models predictive properties by increasing the number of pressure sensors were investigated by traversing a single pressure sensor from the top to the bottom of the gravity separator. It was important to first of all to investigate the effect of measurement noise on the pressure profile by simulating the operation of the gravity separator. The data set obtained from the simulation program was used to assess the ability of the model to accurately estimate the gas/liquid and oil/water interface levels in the gravity separator.

The experimental facility was a pilot scale vertical gravity separator equipped with buffer tanks, pumps, sensors, and a data acquisition system. The separator was cylindrical in shape, made from transparent plastic, 110 cm in height and with 20 cm internal diameter. Four pumps, which can be run independently, were used to pump water or oil into or out of the separator (i.e. two pumps for each single phase). The water output is located slightly above the bottom of the separator whilst the oil output is located about 42 cm from the bottom of the separator. A measuring tape was glued to the plastic gravity separator. This enables visual reading of the gas/liquid and oil/water interface levels. These readings were considered as the reference gas/liquid and oil/water interface level measurements. The experiments were conducted with tap water and model oil (Exxsol D 60) with density of 790 kg/m^3 measured at 15 ^oC. The absolute pressure sensor was connected to a thin flexible cable approximately 2 m in length (Fig. 1). The pressure profiles were acquired by using NI USB-6218 data acquisition device. The starting position of the pressure sensor was 900 mm measured from the bottom of the separator. A stepper motor was used to drive the axle, in this way precise and reproducible levels of the sensor can be achieved.

The operation of the vertical gravity separator was also simulated in Matlab to achieve pressure measurements without measurement noise. Prediction results based on both simulated and measured pressure measurements were compared to assess the effect of measurement noise on the experimental data sets. If the prediction error from models calibrated with this simulated data set is within acceptable limits, the results from the experimental pressure measurements may be improved upon by reducing the impact of measurement noise. In this Matlab simulation program, two sets of 50 random interface levels were generated between the minimum and maximum levels for oil and water (Table 1). An assessment of both the OLS-R and PLS-R methods were carried out from the experimental pressure profiles in relation to estimating the gas/liquid and oil/water interface level measurements. The PLS-R models were calibrated and validated in Unscrambler® whilst the *polyfit* function in Matlab® was used for the OLS-R modelling.

2.2 Partial least squares regression

Partial least square regression was used for calibration of liquid level, oil thickness and water level models based on the pressure profiles obtained from traversing the pressure sensor. The theory, principles and application of PLS-R can be found literature [16,17], and thus only a brief description of this technique will be presented. PLS-R is a statistical data modelling technique which aims at finding an empirical model that relates a matrix (**X**) and reference vector (**y**). The model finds the linear relationship between **X** and **y** data sets. The significance of PLS-R has gradually grown in many fields including physical, pharmaceutical, analytical chemistry and industrial process monitoring and control [17]. In PLS-R, the **y** variable is used to guide the decomposition of the **X** matrix and thus balances the information in both **X** and **y** resulting in reduction of irrelevant PLS components in the calibrated model [16]. 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** data matrix in order to describe the **y** response variable [17]. In evaluating the regression model the root mean squared error of prediction (RMSEP), offset, slope and correlation coefficient are commonly used. The RMSEP for a single response variable is calculated as:

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

Besides these, visual evaluation of the relevant score, loading weights, explained variance plots also provide useful information for calibrating and development of the prediction model. The loading weights and the residual validation variance plots were the main figures considered in the discussion of the results besides the predicted vs. measured plot. The larger the loading weights the more important that measurement is to the model. From the residual validation variance plot, the optimum number of PLS components can be identified. In the PLS-R variance plot, the variance decreases from the first PLS component to a point where the difference between the component n and (n+1) component is negligible. Component n is then considered as the optimum. Increasing the number of PLS components from this point onward would result in modelling measurement noise.

2.3 Ordinary least squares regression

In least squares regression (OLS-R), the *polyfit* function in Matlab® was used to find the coefficient of a line that fits a set of data points in the least square sense. Fig. 2 shows a plot of a pressure profile for a complete cycle of measurements. A clear symmetry was observed from the pressure profile which indicated a high degree of reproducibility of the pressure measurements from traversing the pressure sensor in the separator. The measurements from the pressure sensor while the sensor was moving in the downward direction in the separator were considered in these investigations. It is also possible to select the pressure measurements from the upward direction, thus either the downward or upward pressure measurements could be selected.

The starting position of the pressure sensor was always in air (on top of the separator) this means that pressure measurements with average magnitude of 0 mbar was measured until the medium changed from air to liquid. Fig. 3 shows a plot for one of the measurements where only the downward pressure measurement were considered for pictorial illustration of this technique. A line with slope of 0 was drawn from the beginning of the pressure measurements to the end. Two other lines, one each for fitting the linear function for oil and water were extended to the whole plot area. The intercept of the oil and water linear functions represents the oil/water interface level, whilst that between the line with slope 0 and the oil function corresponds to the gas/liquid interface level. In cases where the separator contains either only oil or only water (not considered in this study), the oil/water interface level can still be estimated. Identification of the type of fluid in the separator can be accomplished by calculating the slope of the linear function. The slope will thus provide the needed information to distinguish between the two liquids.

Another way of tackling this least squares regression technique was by averaging the upward and downward measurements, since both the upward and downward measurements were obtained under the same experimental conditions. An arithmetic mean of the two pressure profiles (upward and downward pressure profiles) was computed. The mean pressure profiles were then considered as the input to the OLS-R technique for estimating the gas/liquid and oil/water interface levels.

3 Result and discussion

All models presented and discussed in this section were validated with independent data sets which were not used to calibrate the models. Models were calibrated for estimating the gas/liquid and oil/water interface levels in the pilot scale gravity separator. Mean centering and variance scaling of the sensor measurements were the two data pre-processing techniques deemed necessary in these investigations. Two regression modelling techniques (PLS-R and OLS-R) were assessed based on their RMSEP.

3.1 Comparison between simulated and experimental data sets

Estimation of gas/liquid and oil/water interface levels in a pilot scale gravity separator was first of all investigated by simulating the operation of the gravity separator to establish the degree of accuracy of the prediction models.

Gas/liquid interface level estimation

In an ideal situation, 1 PLS component is required to differentiate between the gas and liquid phases (i.e. estimate the gas/liquid interface level) in the separator. From evaluating the residual **y** validation variance plot (Fig. 4 upper left), 1 PLS component was optimum to calibrate a model capable of estimating the gas/liquid interface level. From this model, 97%

and 98% respectively of the **X** (pressure measurements) and **y** (gas/liquid interface level) were explained by the model which signifies that almost all the information in both the **X** and **y** data were explained by the model. The RMSEP, slope and R^2 from the model to estimate the gas/liquid interface level within the experimental range (Table 1) was 12.82 mm, 1.00 and 0.99 (Fig. 7 lower left). The high correlation coefficient between the predicted and measured gas/liquid interface level revealed the strong linear relationship that existed between the pressure measurements and the response variable.

It must also be noted here that no outliers were removed from the data. From the same figure (Fig. 4, right), the model from the experimental pressure measurements are presented as an aid in comparing the measurements obtained by simulating the operation of the gravity separator and those obtained from the experimental facility. 1 PLS component was again considered ideal to calibrate a model capable of estimating the gas/liquid interface level (Fig. 4 upper right) with RMSEP, slope and R^2 of 14.51 mm, 1 and 0.98 respectively (Fig. 4 lower right). The difference in prediction error between the simulated and experimental data sets was within the same range with the results from the simulated data set slightly better than the experimental data set. This was expected since there were a bit of measurement noise in the pressure measurements obtained during the experimental process. A prediction error of 14.5 mm in estimating the gas/liquid interface level was considered acceptable.

From Fig. 5, a clear symmetry in relation to the upward and downward sensor movement was observed. The loading weights (Fig. 5) start to increase when the pressure sensor touches the liquid phase. Inside the liquid, the loading weight increases in a form of a non-linear function until the pressure sensor gets to the bottom of the separator. From this point an inverse relation with respect to the downward direction was observed. It can be deduced that only one directional movement (half of a cycle) of the pressure sensor (either upward or downward) can be considered for model calibration to estimate the gas/liquid interface level. These results show that traversing a pressure sensor from the top to the bottom of the vertical gravity separator leads to a more accurate prediction results.

Oil/Water Interface level estimation

Models calibrated from both the experimental data sets and those obtained by simulating the operation of the gravity separator were investigated with the oil/water interface level as the response variable are presented and discussed. Fig. 6 shows the predicted vs. measured oil/water level estimation as an aid for model comparison and evaluation. From this figure, the RMSEP, slope and R^2 for both the simulated and experimental data sets are presented.

Four PLS components were considered optimum to calibrate models capable of predicting the oil/water interface level. During the model calibration process, 5 samples were considered outliers and were subsequently removed from the data. With four PLS components 99% and 96% of the information in the **X** (pressure measurements) and **y** (oil/water interface level) were explained by the model. The correlation coefficient was estimated as 0.96 which meant that the relationship between the predicted and measured oil/water interface level was strong. The difference between the model from the simulated data and that from the experimental data sets was not profound (i.e. 2.5 mm in relation to the RMSEP). This meant that the measurement noise in the experimental data set was within acceptable boundaries. A 17.66 mm oil/water interface level estimation error was considered a promising result in relation to the robust experimental design adopted in these investigations.

3.2 Partial least squares regression and ordinary least squares regression model assessment

A comparison between partial least square regression and least squares regression techniques were investigated from models calibrated with pressure measurements obtained from the experimental design presented in Table 1. The first step was to compare the results from the PLS-R modelling for both upward and downward pressure profiles with that of the OLS-R approach. The RMSEP for the final models from PLS-R and OLS-R techniques are presented in Table 2. From this table, the gas/liquid interface level estimation error from the OLS-R modelling was slightly better than that from PLS-R. In contrast, the oil/water interface level estimation error was greater than those from PLS-R. In calibrating models based on PLS-R technique, outliers were removed from the data matrix which could not be performed in the OLS-R approach. Outliers in the data matrix increased the prediction error thus resulting in a high prediction error in the OLS-R technique. Secondly, in cases where the water level and oil thickness were high, increasing the number of measurement points for fitting the linear function resulted in a better oil/water interface level estimation. Finally, the measurement noise in the data accounted for the increase in uncertainty in fitting the linear function to the pressure measurements.

The results presented in Table 3 were obtained after the pressure profiles were pre-processed. The pre-processing techniques applied include computing the arithmetic mean of the downward and upward pressure profiles and subsequently applying a moving average with varying window sizes. On comparing the results for estimating the gas/liquid interface level from a complete cycle (Table 2) with those from Table 3 based on the RMSEP with respect to OLS-R approach, it was clear that applying a moving averaging on the pressure profiles improved the accuracy of the prediction model. Computing the arithmetic mean removed some of the measurement noise in the data which is a usual phenomenon in data analysis and signal pre-processing. Similar conclusions can be drawn in relation to the magnitude of the prediction error with respect to estimating the oil/water interface level. Several rectangular window sizes for computing the moving average were considered which improved the models predictive ability substantially. From the presented results (Table 3) the threshold for selecting the window size for computing the moving average was 21 selected based on the RMSEP of the calibrated models. The larger the rectangular window sizes the higher the tendency of including irrelevant information to the model. This was in conformance with the experimental design presented in Table 1 where the predefined minimum oil thickness in these investigations was 40 mm. The conclusion that can be drawn from comparing the PLS-R and the OLS-R was that, averaging the measurements can results in a better gas/liquid interface level estimation as compared to the PLS-R method but the other important measurement (i.e. oil/water interface level) was not accurately predicted. Thus the PLS-R technique provided the better overall results and is recommended in subsequent implementation of this measurement technique in estimating both the gas/liquid and oil/water interface levels in industrial gravity separators.

4 Conclusion

The results from models calibrated with a simulated and experimental data sets for a single pressure sensor traversed from the top to the bottom of the separator showed satisfactory results in relation to estimating the gas/liquid and oil/water interface levels in the gravity separator. On assessing the results from PLS-R and OLS-R techniques in estimating gas/liquid and oil/water interface levels, the PLS-R method was deemed better overall and thus recommended in future adaptations of this technique in an industrial scale gravity separator. These satisfactory results coupled with the advantages (cost effective, environmentally friendly, accurate and simple to install gas/liquid and oil/water interface level measurements) that this technique possesses shows a bright prospect for their production and development in commercial scale after further investigations in a continuous flow gravity separator.

References

[1] K. Aleklett, M. Höök, K. Jakobsson, M. Lardelli, S. Snowden, B. Söderbergh. The Peak Of The Oil Age- analyzing the world oil production Reference Scenario in World Energy Outlook 2008. Energy Policy 38 (2010) 1398-1414

[2] M.B. Holstad, G.N. Johansen, P. Jackson, K.S. Eidsnes, Scattered gamma radiation utilized for level measurements in gravitational separators, IEEE Sens. J. 5 (2005) 175-182

[3] S.F.A. Bukhari, W. Yang, Multi-interphase level sensors and new developments in monitoring and control of oil separators. Sensors 6 (2006) 380-389

[4] B.T. Hjertaker, G.A. Johansen, P. Jackson, Level measurement and control strategies for subsea separators, J. Electron. Imaging 10 (2001) 679-689

[5] J. Behin, M. Aghajari, Influence of water level on oil-water separation by residence time distribution curve investigations, Sep. Purif. Technol. 64 (2008) 48-55

[6] V.E. Sakharov, S.A. Kuznetsov, B.D. Zaitsev, I.E. Kuznetsova, S.G. Joshi, Liquid level sensor using ultrasonic lamb waves, Ultrasonics 41 (2003) 319-322

[7] S.E. Woodard, B.D. Taylor, A wireless fluid-level measurement technique, Sens. Actuators A, 137 (2007) 268-278

[8] L.S.L. Fernandes, J.B.A. Paulo, J.A. Oliveira, Development of a strategy to monitor and control the oil-water interface level of a liquid-liquid separator for treatment of waste water using an image-based detector, 10th international symposium on process systems engineering-PSE2009, 1269-1274

[9] C.-W. Lai, Y.-L. Lo, J.-P. Yur, W.-F. Liu, C.-H. Chuang, Application of Fabry-Pérot and fiber bragg grating pressure sensors to simultaneous measurement of liquid level and specific gravity, Measurement 45 (2012) 469-473

[10] N.-O. Skeie, S. Mylvaganam, B. Lie, Using multi sensor data fusion for level estimation in a separator, 16th European symposium on computer aided process engineering and 9th international symposium on process systems engineering 2006; 1383-1388

[11] N.-O. Skeie, M. Halstensen, Level estimation in oil/water separators based on multiple pressure sensors and multivariate calibration, J. Chemom. 24 (2010) 387-398

[12] N.-O. Skeie. Soft sensors for level estimation. PhD thesis, The Norwegian University of Science and Technology (NTNU), 2008, ISBN: 978-82-471-4462-6

[13] A.J. Jaworski, G. Meng, On-line measurement of separation dynamics in primary gas/oil/water separators: Challenges and technical solutions- A review, J. Petrol. Sci. Eng. 68 (2009) 47-59

[14] W. Yang, Sensors and instrumentation for monitoring and control of multi-phase separation, Meas + Control 39 (2006) 178-184

[15] W. van de Kamp, The theory and practice of level measurement 22nd ed. Endress+Hauser, Naarden, Holland, 2008

[16] H. Martens, T. Næs, Multivariate Calibration, 2nd ed., vol.1, Wiley, Chichester 1989, pg 73-232

[17] P. Geladi, B.R. Kowalski, Partial Least Square Regression: A Tutorial. Anal Chim Acta 185 (1986) 1-17

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Table 2. Gas/Liquid and Oil/Water interface level model comparison with PLS-R and OLS-R techniques

Table 3. RMSEP from applying moving average with varying rectangular window sizes to improve the models predictive properties in the OLS-R approach

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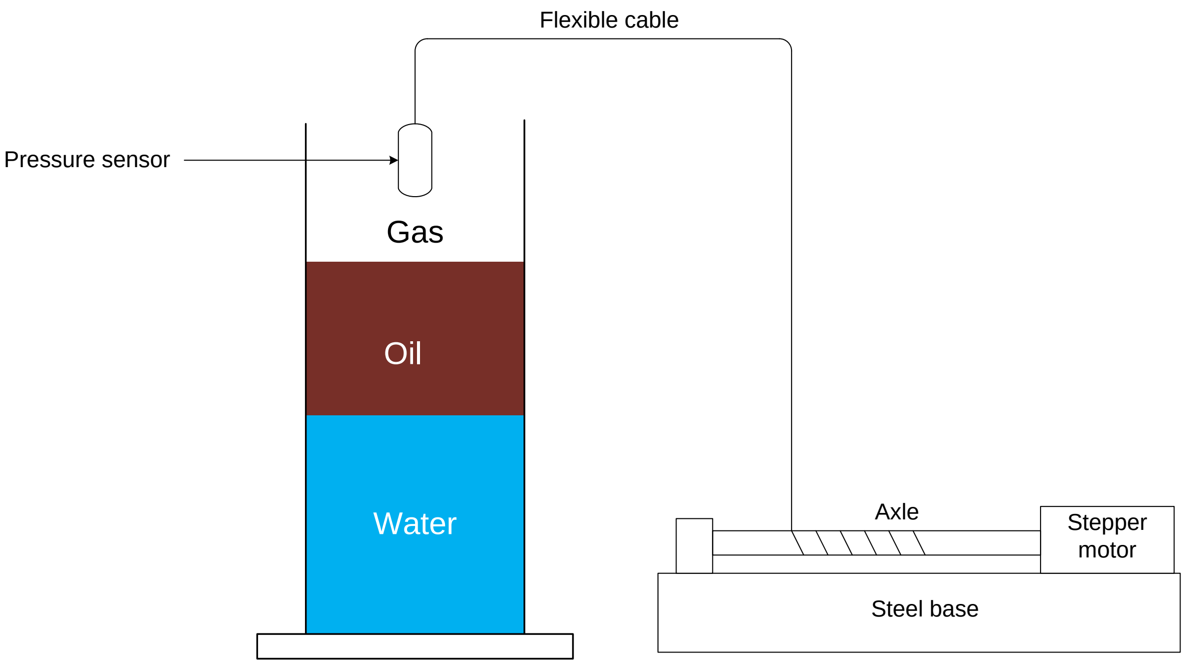

Fig. 1. Experimental test facility with a stepper motor for traversing the pressure sensor from the top to the bottom of the separator and in a reverse cycle for each experimental run

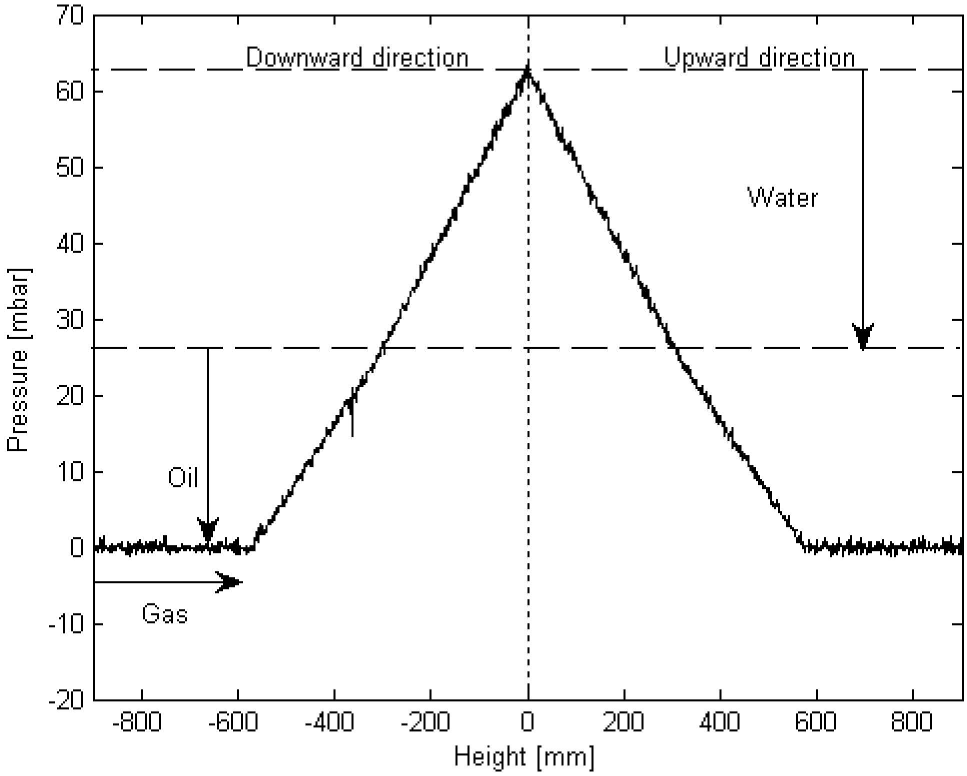

Fig. 2. Pressure profile for a complete cycle of movement of the pressure sensor in the vertical gravity separator

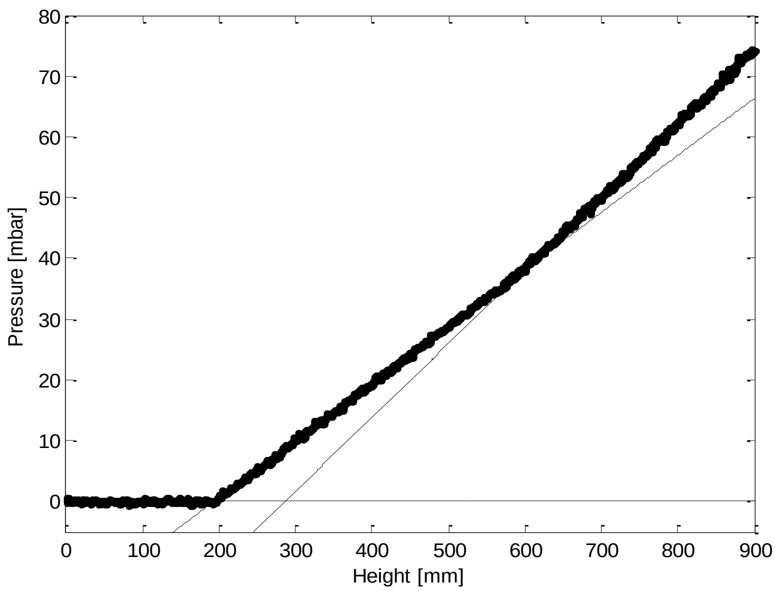

Fig. 3. Application of ordinary least square regression for determining the gas/liquid and oil/water interface levels in a gravity separator considering only downward pressure profile.

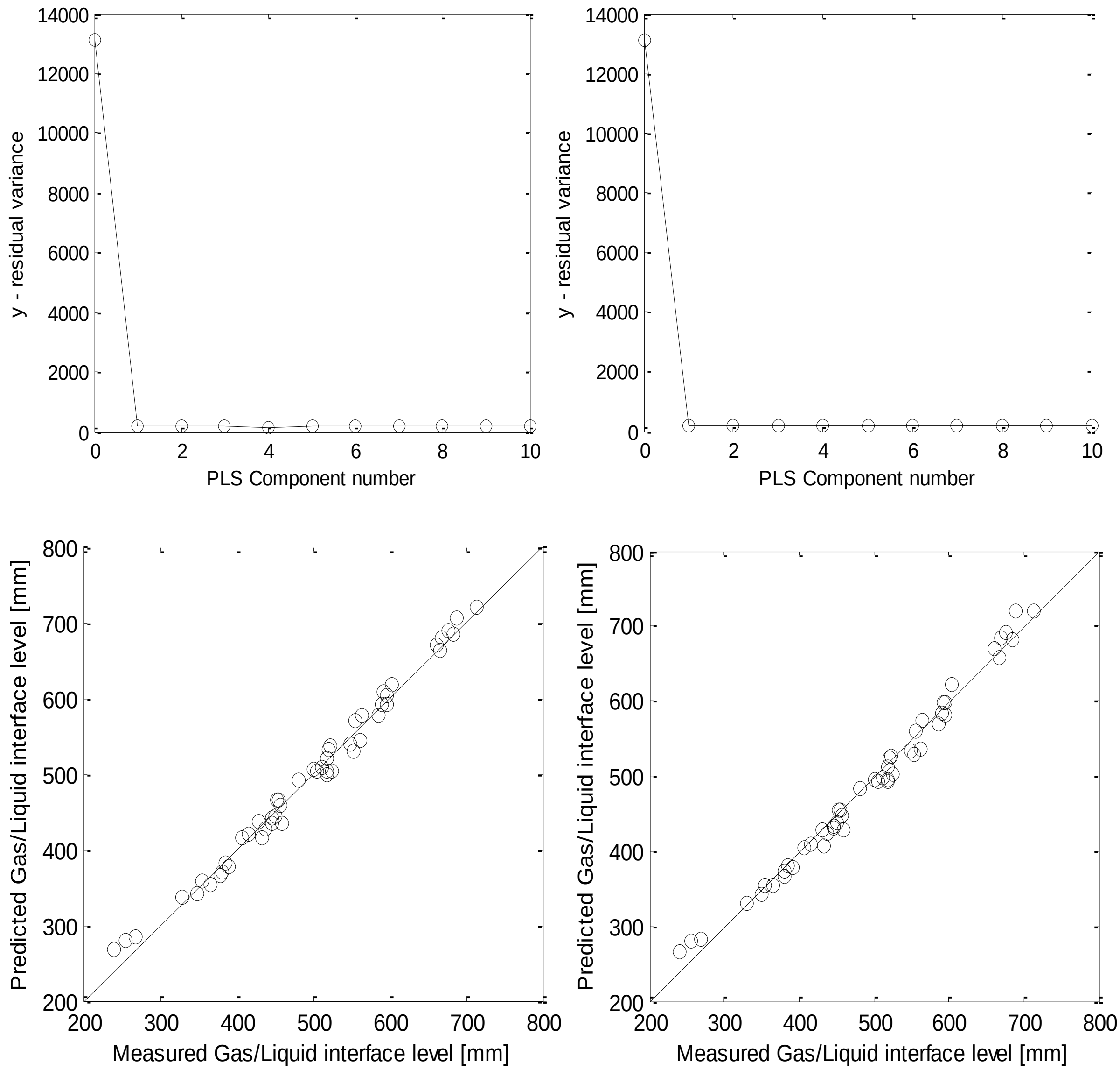

Fig. 4. Liquid level estimation comparison between simulated and experimental data sets. Left: Simulated data, Right: Experimental data, Upper: Residual validation variance plot, Lower: Predicted vs. measured plot.

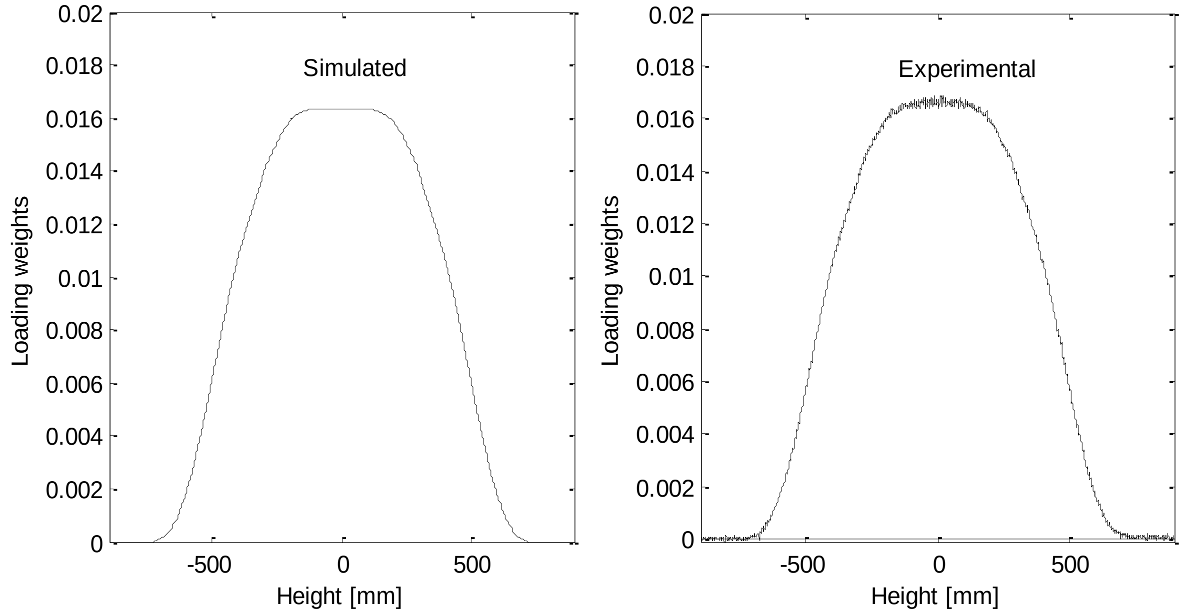

Fig. 5. Comparing the loading weight plots for both simulated and experimental data for PLS component 1. The two plots shows identical profiles but the experimental data also includes some measurement noise which can be observed also in the loading weights.

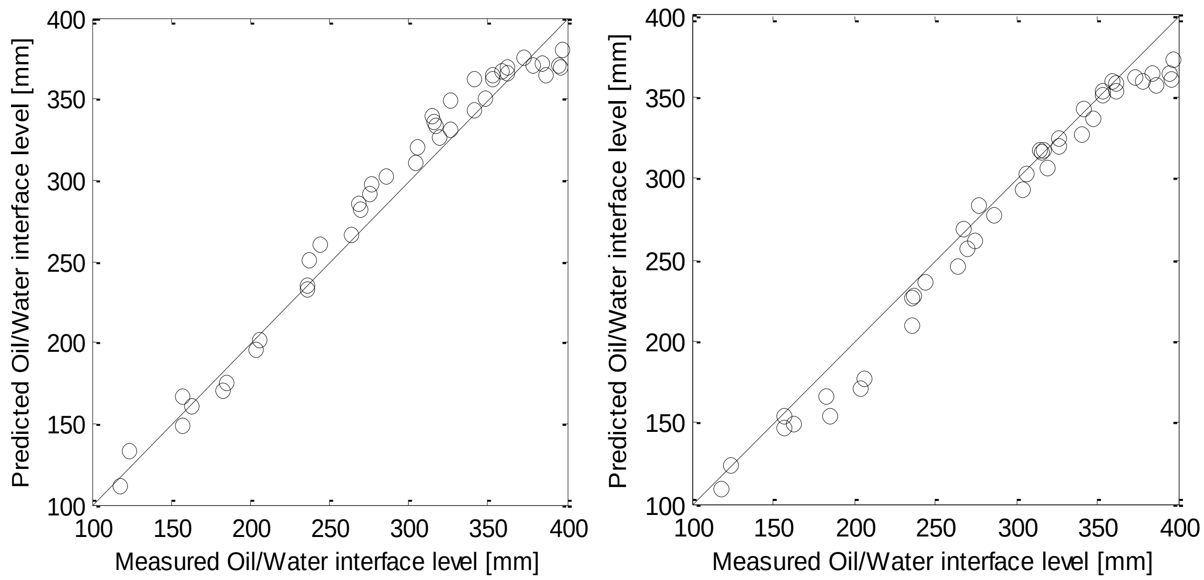

Fig. 6. Comparing the Oil/Water level models predictive properties for the simulated and experimental data sets. The predicted vs. measured plots are shown as an aid for this comparison. Left: Simulated data set. Right: Experimental data set

Tables

Table 1. Minimum and maximum oil and water levels adopted in experiments for comparing models from both simulated and experimental data sets.

	Oil Thickness (mm)	Water Level (mm)
Minimum	40	105
Maximum	400	420

Table 2. Gas/Liquid and Oil/Water interface level model comparison with PLS-R and OLS-R techniques based on RMSEP

RMSEP from OLS-R		RMSEP for PLS-R	
Gas/liquid (mm)	Oil/water (mm)	Gas/liquid (mm)	Oil/water (mm)
13.5	42.99	14.51	17.66

Table 3. RMSEP from applying moving average with varying rectangular window sizes to improve the models predictive properties in the OLS-R approach

RMSEP, Least Squares Method		
Window size	Gas/Liquid interface (mm)	Oil/water interface (mm)
0 (no smoothing)	10.92	28.09
11	10.82	26.83
21	10.82	26.88
31	10.90	27.88
51	10.92	26.66
201	11.11	61.39
301	11.33	199.04